International Journal of Energy Production and Management
Vol. 10, No. 2, June, 2025, pp. 175-182
Journal homepage: http://iieta.org/journals/ijepm

The Impact of Engine Speed on Performance and Emission Characteristics of Engine Fueled with Diesel-Water Emulsion

Louay A. Mahdi[1], Hasanain A. Abdul Wahhab[2], Yasmeen H. Abed[3], Miqdam T. Chaichan[1], Mohammed A. Fayad[1*]

[1] Energy and Renewable Energies Technology Center, University of Technology- Iraq, Baghdad 10066, Iraq
[2] Training and Workshop Center, University of Technology- Iraq, Baghdad 10066, Iraq
[3] Mechanical Engineering Department, University of Technology- Iraq, Baghdad 10066, Iraq

Corresponding Author Email: mohammed.a.fayad@uotechnology.edu.iq

https://doi.org/10.18280/ijepm.100202

Received: 12 December 2024
Revised: 11 February 2025
Accepted: 24 March 2025
Available online: 30 June 2025

Keywords:
diesel-water emulsion, CO_2 emission, sulfur, PM-NO_X trade-off, SO_2, UHC

ABSTRACT

Many studies have suggested various techniques to replace fossil fuel, including diesel, whose combustion emits exhaust pollutants which in turn lead to a risk to the environment and public health. The combustion of water-diesel emulsions can emit fewer exhaust pollutants when fueled by a diesel engine. In Iraq, Iraqi crude oil is characterized by a high percentage of sulfur in it, which makes all its derivatives contain sulfur percentages. Iraqi diesel sulfur content ranges from 1% to 2.5%. Sulfur causes an increase in some dangerous pollutants, such as sulfur oxides. If these oxides combine with the emissions of nitrogen oxides (NO_X) and unburned hydrocarbons in the atmosphere, they will cause smog clouds with significant health and environmental risks. In this experimental study, the performance of a diesel engine was investigated at constant load and variable speed of the engine, using three types of emulsions (water-diesel). Brake-specific fuel consumption (BSFC) is reduced when working with 10% and 20% water emulsions. In contrast, 30% of water emulsion consumption was increased. The NO_X emissions declined by 14%, 16%, and 29% for emulsions 10%, 20%, and 30% water added to diesel, respectively. As for hydrocarbons, they decreased by 1% and 9.3% in the case of adding 10% and 20%. Hydrocarbon levels increased by about 33.6% when 30% water was added to diesel. Experiments have shown that both NO_X and PM decrease together when using 10% and 20% emulsions.

1. INTRODUCTION

The term emulsion is derived from the Latin word 'emulate', which means to milk out. As we know, milk is a classic example of an emulsion of fat in water, where fat globules are dispersed into the continuous phase of milk, which is water. The emulsion can be considered as a two-phase system. It is a thermodynamically unstable system and tends to separate over time. When the emulsified liquid is allowed to settle (under static conditions), because of the differences in densities of the two liquids, the lighter phase will rise to the top, and the heavier phase will settle on the bottom, eventually coalescing with the main continuous phase and separating altogether. This process is governed by Stokes's law, which is directly affected by the sizes of the dispersed phase [1]. The larger fluid volume leads to faster coalescence, while the difference in the densities and viscosities of the two phases accelerates the separation process. A lower viscosity of the continuous phase provides less resistance to the motion of the dispersed phase. However, this phase separation can be prevented if some external forces are continuously applied (under dynamic conditions) to the liquid to disperse the dispersed phase evenly into the continuous phase. This process is known as homogenization. This type of emulsion is known as a permanent emulsion, which is one of our main objectives for developing diesel emulsion because it can be stored and used for a long time [2].

The emulsion of diesel with water can be explained as the mixing of two immiscible liquids, where diesel particles are the discrete phase, and water is the continuous phase. The same theory is applied when air mixes with diesel fuel in the combustion chamber, where atomized diesel fuel is the discrete phase and air is the continuous phase [3]. By applying external force (compressed air from a turbocharger), it is possible to atomize the diesel fuel into fine droplets and disperse them evenly into the air. This method can be considered as homogenization in a direct injection diesel engine [2]. The combustion of emulsified diesel is divided into two phases. Primary combustion is initiated when emulsified diesel comes into contact with the hot compressed air inside the combustion chamber, causing the water in the diesel to change state into steam, which expands rapidly in all directions and causes the diesel particles to be propelled against the wall of the cylinder [4]. The rapid expansion of the steam can cause the diesel particles to be pushed away from the fire due to more space involved. This will cause the incomplete combustion of the diesel, delaying the ignition and extinguishing as the diesel particles are trapped by the droplets of the steam [5]. This cycle will result in more smoke being produced from the combustion. Secondary combustion is initiated when the steam escapes from the fire and mixes with the air, causing the diesel particles to re-ignite a new fire around the entry of the combustion chamber. This ignition will burn or oxidize the smoke particles, which are hydrocarbons, into CO_2 and H_2O. It is less toxic and better for the environment [6].

Adding water to diesel is considered an effective way to control nitrogen oxides (NO_X) formation. The presence of water and diesel in the combustion chamber results in a clear reduction in the temperature inside the chamber. This is due to the absorption of thermal energy to provide the latent heat of evaporation necessary for water [7]. This decrease in temperature will reduce the emissions level of NO_X inside the cylinder. The ignition delay also increases in this case, resulting in higher pre-mix levels and decreased soot formation [8]. In addition, water atoms within the fuel are dispersed due to premature evaporation. This causes a rise in the temperature of the drop and a sudden increase in the volume of water vapor. This rapid expansion is known as a micro-explosion, and this micro-explosion causes the fuel droplet to rupture, generating smaller fuel fragments [9]. This process enhances air-diesel mixing and minimizes PM formation. Gowrishankar and Krishnasamy [10] confirmed that water-diesel emulsions decrease both NO_X and PM emissions. It is stated that the blend of water-diesel emulsions can reduce BSFC [11]. Emulsions are also more cost-effective and can be used in existing engines without modification. Furthermore, emulsions reduce the energy content of the fuel, resulting in lower fuel consumption and emissions [12].

Water fuel emulsion is one of the fuel alternatives that has great potential to solve the problems in the combustion process and emissions. The emulsion is a mixture of water and diesel fuel that is stabilized using various additives and mechanical/emulsification processes [13]. Most emulsion research workers said that this emulsion has the potential to reduce emissions without sacrificing engine performance [14]. Several researches have been conducted to investigate the performance and emissions of engines fueled by emulsion fuel [15]. But the results are varied and one of the reasons is the use of many kinds of emulsion fuels. Most of them are using emulsion with a small amount of water because a high percentage of water in the emulsion will cause several problems in engine combustion and fuel injection systems [16]. So, it needs to be distinguished from an emulsion that uses a large amount of water, which is called a "water fuel emulsion".

Any diesel-water emulsion consists of two liquids that are incompatible in terms of density and viscosity, so any mixing of them will not be stable, meaning separation will appear between the two liquids [17]. Therefore, all studies in this field adopted the addition of limited amounts of surfactants (surface active agents) to improve the stability of these emulsions [18]. The addition of surfactants reduces surface tension at the interface of the two fluids. This causes a significant decrease in the free energy at the interface, which enhances the emulsion's stability [19]. Perhaps the most famous and most widely used mixtures of different surfactants in studies of this type are Span 80 and Tween 80. These mixtures synergize with emulsion stability. Mekarun et al. [20] mentioned that it is possible to produce a more stable emulsion (in terms of molecular structure and surfactant quality) when mixing both Span 80 and Tween 80 in equal proportions and adding them to the emulsion. This method was also confirmed by Prabhudeva and Karmakar [21], who showed that the use of Span 80 and Tween 80 in the preparation of water-diesel emulsions which it's considered the most common. In this study, surfactant was added to the prepared emulsions in proportions ranging from 1% to 2% (percentage of the total volume of the emulsion).

Water-diesel emulsions have a higher density than diesel, in addition to density, viscosity and flash point increase. The emulsion viscosity increases with the increasing water content. This viscosity decreases rapidly as temperatures inside the combustion chamber rise [22].

Emulsion's stability is considered one of its most significant characteristics. In the event of incompatibility between water and diesel, the emulsion separates into its basic components, and the combustion process deteriorates. Therefore, maintaining a stable emulsion for a long period enables it to be used as fuel. Diesel additives such as water, surfactants, cetane number improve, and mixing methods affect the emulsion's stability.

Researchers typically use low or ultra-low sulfur diesel in their emulsions. In contrast, Iraqi diesel (which is tested in this study) has high sulfur content and has considerable potential to react with the added water to develop the fuel properties that may contribute to corrosion of the fuel container and cause dangerous emissions such as sulfur oxides. An increase in sulfur oxides in the exhaust will interact with the water vapor resulting from combustion. This will form sulfur fumes that threaten the environment and living organisms. Consequently, this study aimed to examine the performance of the diesel engine, and the pollutants emitted from it when fueled with emulsions formed from Iraqi diesel and distilled water. This study also focuses on the relationship between NO_X and PM, as well as sulfur dioxide (SO_2) concentrations.

2. EXPERIMENTAL SETUP

Practical experiments were carried out with a Fiat TD 313 diesel engine with water-cooled direct injection (Figure 1). The four-cylinder 3.666 L, four-stroke engine is equipped with two valves per cylinder and has a compression ratio of 17:1. The motor is connected to a water dynamometer to control the load on the motor by increasing torque. The Aerocet-USA is used to measure PM emissions, and the G460 (made in Germany) is used to measure SO_2 emissions. A microphone was connected to a microphone to measure engine noise using a type 4615 meter. Each experiment was repeated three times, and the average of the measured data was taken for each mixture to ensure high accuracy of the results. The accuracy and unreliability levels of all the above devices were determined before experiments were conducted (Table 1).

2.1 Emulsions preparation

In this practical study, an improved fuel was prepared, which is a mixture of water and diesel with the addition of a surfactant or surface-active agent, based on the previous study [17], and a cetane number improver was also introduced. The mixing process was done by incorporating the cetane number improvement first (1% by volume to 10% water, 1.5% by volume to 20% water, and 2% by volume to 30% water). After this process, a surfactant was added (2% by volume to water). As soon as the previous ingredients have been mixed, they are added to the diesel. This prepared mixture was mixed through an ultrasonic shaker for 90 minutes to ensure complete mixing of water and diesel. This is expected to produce a stable mixture for an acceptable period. In this work, locally available Iraqi diesel fuel and distilled water were employed. Iraqi diesel fuel contains high sulfur levels. The fuel used in the study contained up to 10,000 parts per million (ppm) sulfur. Several samples of the prepared emulsion were sorted, and their stability was checked before being fueled into the engine for experiments. During the tests, a standard injection system (17° BTDC) was used to inject the emulsion into the engine. Table 2 shows the properties of the diesel emulsion blends and their comparison with the diesel-water emulsions utilized in the experiments.

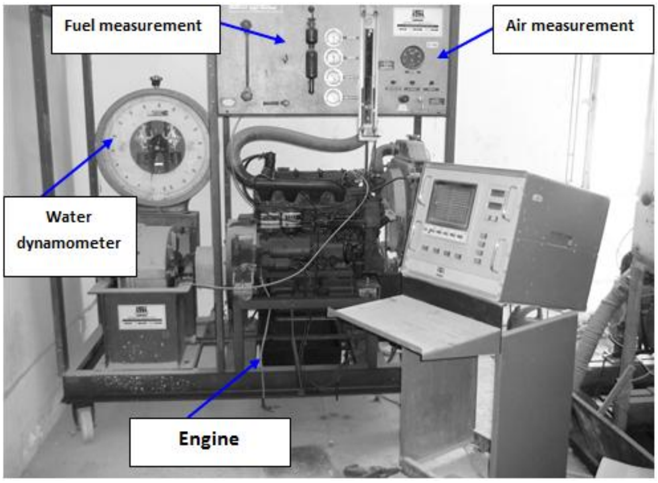

Figure 1. A photo of the used diesel engine in the tests

Table 1. Uncertainties about the used devices and emissions

Measuring Devices	Uncertainty
Thermocouples	0.34
Flow rate meter (air)	0.32
Flow rate meter (fuel)	0.55
Engine speed tachometer	0.76
Dynamometer (torque)	0.79
Engine noise meter	0.57
Emissions Variables	**Uncertainty**
CO concentrations (vol.%)	0.48
HC concentrations (vol.%)	0.33
NO_X concentrations ppm	0.39
SO_2 concentrations (vol.%)	0.36
PM concentrations (μg/m^3)	0.88

The mixture prepared from 10% water and 90% diesel fuel was called W10, and the mixture consisting of 20% water and 80% diesel was called W20. The name W30 was given to the mixture consisting of 30% water and 70% diesel. These emulsions all contained additives that improve cetane number and surfactants, as described in the fuel preparation section. Many physical and chemical changes were detected in the prepared emulsions compared to diesel. Some of them can be observed in Table 2, such as higher viscosity, lower cetane number, and enthalpy. Such changes in fuel properties cause obvious changes in the evaporation characteristics of emulsion spray. This naturally reflects on the quality of the combustion process and the pollutants emitted.

Table 2. Prepared fuels compared to Iraqi diesel specifications

Property	Diesel	W10	W20	W30
Density (kg/m^3)	821	828	839	846
Cetane number	51.45	50.55	50.35	49.6
LHV (MJ/kg)	47.33	46.58	44.24	42.14
Viscosity (cSt)	2.87	3.1	3.21	3.28
Final boiling point (°C)	370	355	347	330
C% (by weight)	87	81	76	70
H% (by weight)	12.08	16	18	20
S% (by weight)	1	0.81	0.62	0.43
N% (by weight)	0.07	0.06	0.055	0.045
O% (by weight)	-	4	6.8	11
Molecular weight (g/mole)	209	200	189	180

2.2 Performance parameters

Engine performance and emissions were evaluated as a function of engine speed at constant load. A constant load and fixed injection timing of 17° BTDC were used in the experiments. The load was fixed at 44 kN/m^2. This average load was adopted in the study because it has been proven that the highest performance can be achieved at such loads with the most efficient exhaust pollutants. It also represents the load of vehicles and cars operating within the city. The following equations were adopted in evaluating engine performance [23]:

1. Brake power

$$bp = \frac{2\pi * N * T}{60 * 1000} \text{ kW} \tag{1}$$

2. Brake mean effective pressure

$$bmep = bp \times \frac{2 * 60}{V_{sn} * N} \text{ kN/m}^2 \tag{2}$$

3. Fuel mass flow rate

$$\dot{m}_f = \frac{v_f \times 10^{-6}}{1000} \times \frac{\rho_f}{time} \text{ kg/sec} \tag{3}$$

4. Air mass flow rate

$$\dot{m}_{a,act.} = \frac{12\sqrt{h_o * 0.85}}{3600} \times \rho_{air} \frac{kg}{sec} \tag{4}$$

$$\dot{m}_{a_{theo.}} = V_{s.n} \times \frac{N}{60 * 2} \times \rho_{air} \frac{kg}{sec} \tag{5}$$

5. Brake specific fuel consumption

$$bsfc = \frac{\dot{m}_f}{bp} \times 3600 \frac{kg}{kW.hr} \tag{6}$$

6. Total fuel heat

$$Q_t = \dot{m}_f \times LCV \text{ kW} \tag{7}$$

7. Brake thermal efficiency

$$\eta_{bth.} = \frac{bp}{Q_t} \times 100\% \tag{8}$$

From the actual value to a certain degree, the measurement of this quantity is considered inaccurate. Error levels are determined using known standard calibration techniques. The process of calibrating and analyzing measurements' reliability is called uncertainty analysis. The presence of uncertainty in calculating a specific quantity within an experiment creates uncertainty for the entire experiment [24]. In this study, the equation to measure uncertainty in the results was used below [24]:

$$e_R = \left[\left(\frac{\partial R}{\partial V_1}e_1\right)^2 + \left(\frac{\partial R}{\partial V_2}e_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n}e_n\right)^2\right]^{0.5} \quad (9)$$

The uncertainty estimated in the final measurements is provided in Table 1, which lists the measuring devices used in the experiments. Based on Eq. (9) and the values of measuring instruments uncertainties presented in Table 1, the maximum uncertainty was less than 3%, which indicates high quality and accuracy.

3. RESULTS AND DISCUSSION

3.1 Emulsion stability

Table 3 shows the contents of the three emulsions prepared and used in the present study with their stability period. The stabilities of the prepared emulsions are high and last for several days, indicating the successful mixing procedure used.

3.2 Engine speed effect on performance

Figure 2 shows that engine brake power increases moderately at medium speeds but decreases at low or high speeds. In addition, the average increase for W10 is 2.68%, and for W20, it is 3.99%, while the engine brake power is reduced by 4.48% when using W30. The change in speed from low to medium speeds allows better ignition mixture conditions and raises temperatures at combustion chambers, helping heat and combustion efficiency. This is the best finding at W10 and W20, as they raise pressures and temperatures in combustion chambers. The turbulence growth in the chamber is accelerated as the engine speed increases from a moderate level to a high one, which in turn reduces the initial delay period of the preparation of diesel-water emulsion, resulting in a decrease in combustion chamber brake power, particularly for W30, which makes it more difficult to ensure proper combustion. Recent results are in line with the prior work [25].

To increase engine speed, more fuel must be consumed, resulting in higher brake-specific fuel consumption (BSFC), as illustrated in Figure 3. With W10 and W20 emulsions, BSFC decreased by approximately 1.22% and 6.33%, respectively. According to this result, fuel combustion occurs more efficiently in the combustion chamber. In contrast, the BSFC increased by about 4.29% when using W30, which indicates that deterioration can occur in combustion. Results from a previous study [26] are consistent with those obtained from the recent study.

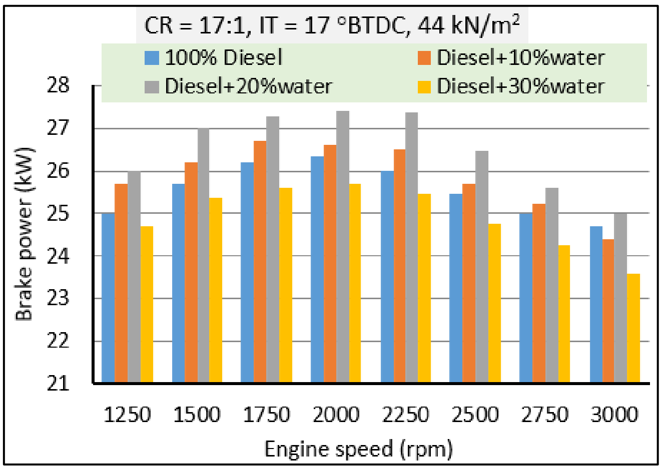

Figure 2. Impact of emulsions on brake power for variable engine speeds

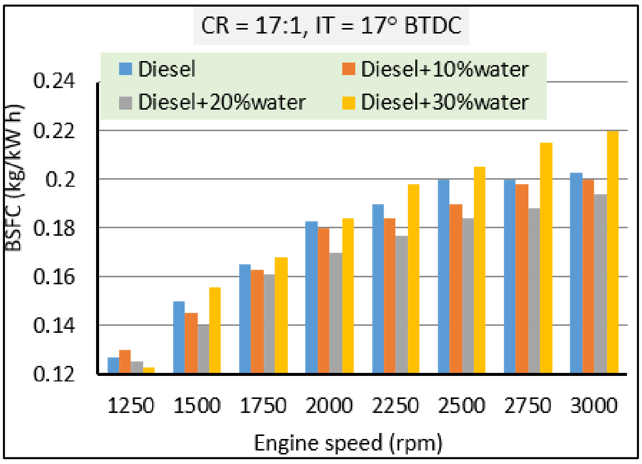

Figure 3. Impact of emulsions on BSFC for variable engine speeds

Exhaust gas temperatures (EGT) decreased when using W10 and W20 and increased when using W30, as Figure 4 shows. Compared to diesel fuel, EGT is reduced by 6.56% and 13.6% under W10 and W20 operating conditions, respectively. EGT increased by approximately 11.11% when the engine ran at W30. The engine took advantage of the heat generated inside the combustion chamber by increasing the pressure on the piston at an ideal time. This resulted in the cooling of the exhaust gases during the expansion stroke and low EGT output, as happened in working with W10 and W20. This result confirms the possibility of using these two emulsions in diesel engines, as they improve BP and BSFC (Figures 2 and 3). As for W30, due to its need for a longer delay period, part of it is burned during the expansion stroke. It exists during the exhaust stroke at high temperatures. In this case, the engine does not benefit from the energy released during the expansion stroke. Figures 2 and 3 also show that W30 caused a decrease in motor BP and an increase in its BSFC.

Table 3. Developed and used emulsion sample specifications for the engine tests

Emulsion	Water (vol.%)	Diesel (vol.%)	Span 80 (vol.%)	Tween 80 (vol.%)	Stability (hours)
W10	9.5	89.5	0.5	0.5	153
W20	19.25	78.25	0.75	0.75	148
W30	39	69	1.0	1.0	131

The above results show that the highest engine performance was when running an engine with W10 and W20 fuel. Both emulsions were used without changing the engine's fuel system or other parts. From what has been mentioned, it can be inferred that there is a real possibility of running the engine with either W10 or W20. This is done by injecting the fuel blended directly into the combustion chamber without any added modifications to the engine.

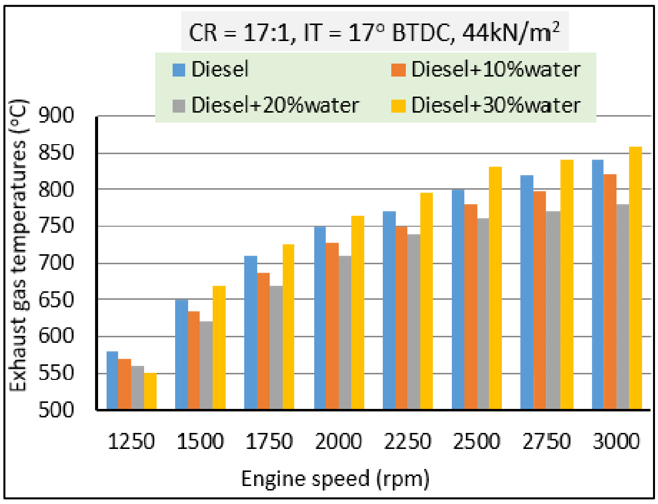

Figure 4. Impact of emulsions on EGT for variable engine speeds

3.3 Engine speed effect on emissions

Operating the engine with the tested emulsions caused a decrease in NO_X levels, as shown in Figure 5. These concentrations decreased by 14%, 16%, and 29% for W10, W20, and W30, respectively. NO_X requires three basic factors in the combustion chamber to form. These factors are the presence of sufficient oxygen, a combustion temperature higher than 950 degrees Celsius, as well as the time required for formation [27]. Therefore, when the engine is operated with emulsions with a high percentage of oxygen in their content, combustion is improved. This raises combustion chamber temperatures and facilitates NO_X formation. However, this picture is not complete, as the emulsions absorb the heat of their evaporation from inside the combustion chamber. This reduces the overall temperature of this chamber, which limits NO_X formation [28]. Many research studies have confirmed that water-diesel emulsions reduce NO_X emissions [29]. By increasing the engine speed, the amount of fuel burned increases and thus the amount of heat released into the combustion chamber. This increases NO_X emissions concentration inside the cylinder and through the exhaust pipe. However, when working with a water-diesel emulsion, NO_X concentrations decrease, and they decline higher as the percentage of water in the emulsion increases. The water in the emulsion absorbs a large portion of the combustion chamber heat for evaporation. This decreases the combustion chamber temperature, reducing oxide formation. When comparing NO_X levels with diesel levels, it is noted that working with W10, W20, or W30 caused a reduction in NO_X concentrations by approximately 9.2%, 19.66%, and 27.63%, respectively. These results from the current study are consistent with the work by Ithnin et al. [29].

Figure 6 shows the effect of running the engine with the tested emulsions on PM levels emitted by the engine. PM levels were reduced when working with all the tested emulsions. The average reductions in PM were 18.7%, 26.9%, and 44.7% for W10, W20, and W30, respectively, compared to diesel. The presence of water in the fuel enhances partial explosion, which increases the oxidation reactions of PM. The presence of water also causes the flame temperature to drop. The water in the fuel also acts as a source of oxygen. This causes the fuel-to-air ratio to change during the pre-mixing period, making it an environment richer in oxygen than less fuel, which greatly helps soot oxidation. These results are consistent with previous experimental results of Dhinesh et al. [30].

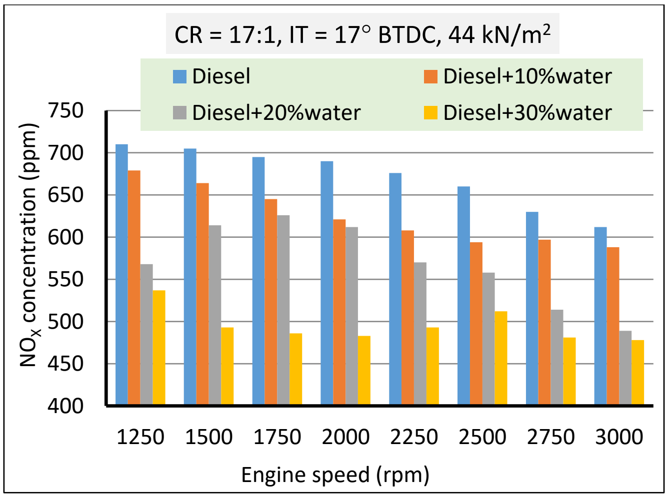

Figure 5. Impact of emulsions on NO_X levels for variable engine speeds

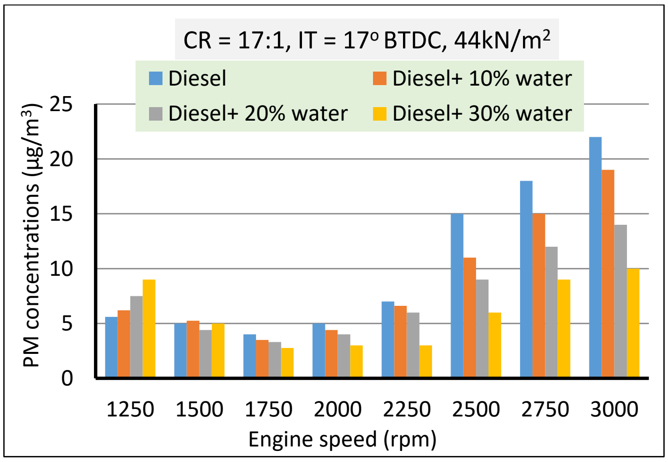

Figure 6. Impact of emulsions on PM levels for variable engine speeds

Studies of pollutants emitted from the engine are interested in the comparison between NO_X and fine particles, as decreasing the emissions of NO_X by any technique will increase PM concentrations and vice versa. It is not easy to use a single technology that reduces both pollutants together. Figure 7 shows the potential of the prepared emulsions to reduce PM and NO_X levels together compared to diesel. The results show that the greatest reduction is in the working condition at W30, followed by W20, then W10. It can be asserted that the unmodified engine can operate on W20 and W10 fuel. However, if using W30, fuel injection timing must be adjusted to improve combustion and performance. The study confirms that W20 is the most effective emulsion of those prepared in the study. This enables the reduction of NO_X and PM pollutants together without modifications to the engine. This study's results are consistent with those in the work by Khalife et al. [31].

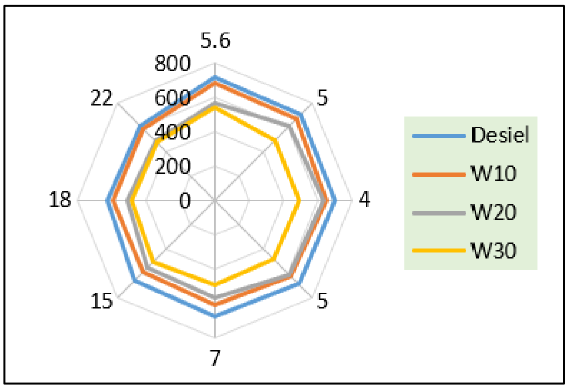

Figure 7. Impact of emulsions on PM-NO_X trade-off for variable engine speeds

Figure 8 shows the effect of working with the tested emulsions on carbon monoxide (CO) concentrations. These concentrations decrease when the engine runs at medium speeds and increase at slower and higher speeds. CO levels decreased at 10W and W20 and increased at W30. The presence of CO concentrations in the exhaust is evidence of incomplete combustion and a lack of local homogeneity of air and fuel. This uniformity is affected by the insufficient turbulence inside the combustion chamber at low speeds and by the excessive turbulence at high speeds. CO concentrations can be used as a measure of combustion efficiency. Higher CO levels at low and high speeds are an indication of incomplete combustion, while the lower levels at medium speeds are an indication of more efficient combustion. The findings of this study are in line with those reported in previous studies like Ekaab et al. [32] and Sun et al [33].

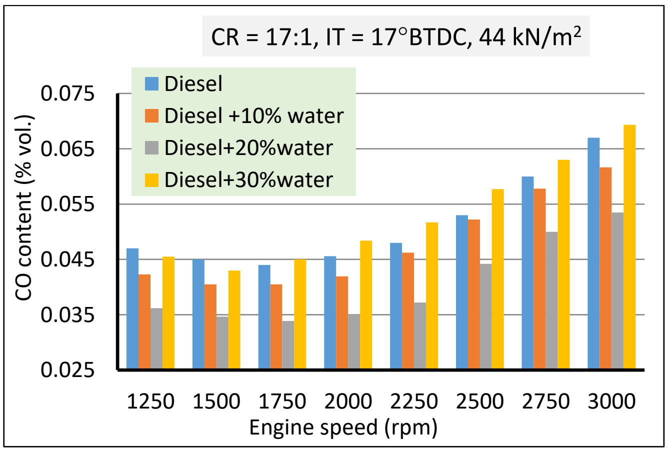

Figure 8. Impact of emulsions on CO levels for variable engine speeds

Figure 9 shows the effect of working with the tested emulsions on HC release levels. HC levels decrease when the engine runs at W10 and W20 by 1% and 9.3%, respectively. Also, it increased when running at W30 by 33.6%. HC concentrations indicate deterioration in engine performance due to incomplete combustion. Therefore, enhancing the engine performance when operating at W10 and W20 reduced HC concentrations. Also, working at W30 caused a deterioration in combustion, reduced engine performance, and increased HC. This indicates that the optimal engine operation is at W10 or W20. Engines operating at W30 should be avoided. Sun et al. [33] reported similar findings.

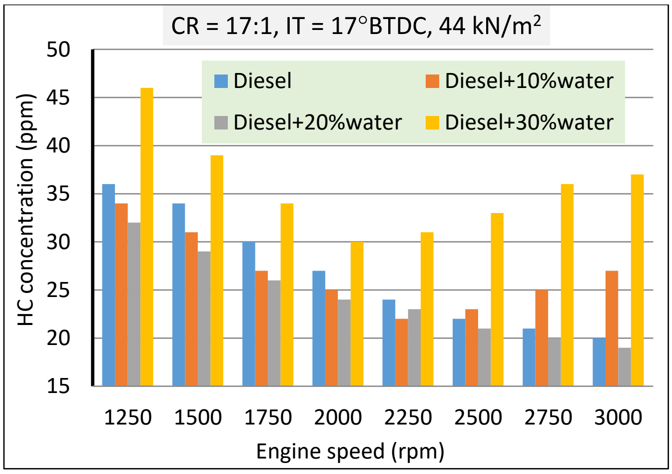

Figure 9. Impact of emulsions on HC levels for variable engine speeds

As a result of the presence of a clear amount of sulfur compounds in Iraqi diesel, when this fuel is burned, varying levels of SO_2 are emitted, as shown in Figure 10. Most researchers working to find alternatives to diesel have not studied this pollutant. This is because most countries deal with using diesel fuel with a very low sulfur content, symbolized by ULSD. A certain percentage of sulfur is usually involved in the nuclei in which carbon atoms are built into PM particles. In this study, the diesel used is produced in Iraq and has a high sulfur content. SO_2 concentrations are evident in exhaust gas. This gas reacts with water vapor in the exhaust, forming sulfuric acid fumes. These fumes are very dangerous to humans, animals, and the environment. Adding water to diesel reduces the sulfur content in the fuel and limits its effects after combustion. When the engine was operated with W10, W20, and W30, SO_2 levels decreased significantly by 10.45%, 17.7%, and 28%, respectively, compared to diesel. SO_2 levels increase due to abundant oxygen, suitable combustion temperatures, and sufficient reaction time.

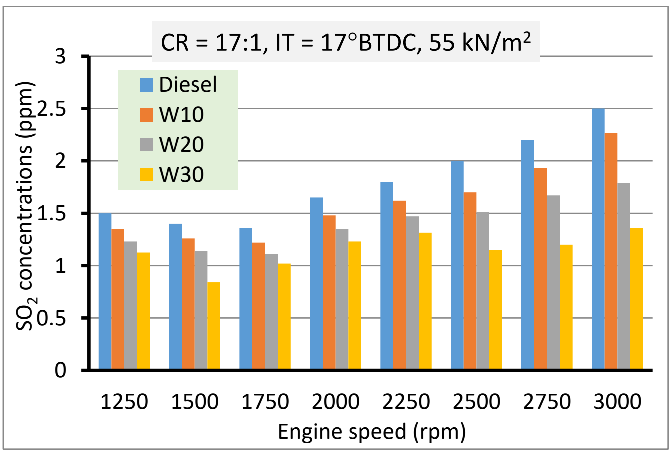

Figure 10. Impact of emulsions on SO_2 levels for variable engine speeds

4. CONCLUSIONS

The current study examines the possibilities of using a diesel-water emulsion fuel with the addition of a cetane number improver and surfactant. The study aims to find a promising way to reduce fuel consumption and engine emissions. The first experiments were to examine the fuel's stability and its lack of separation and to ensure the accuracy and success of the mixing method. The results demonstrated the following:

- High stability of the prepared emulsion types and the possibility of working with them for several days after their preparation.
- There is a possibility of improving engine performance and reducing emissions by water-diesel emulsions.
- The BSFC dropped slightly (1.22% and 6.33%) when the engine was fed with W10 and W20, but increased by about 4.29% when working with W30.
- CO and HC emissions also decreased when the engine ran at W10 and W20 at all engine speeds tested.
- NO_X and particulate matter decreased at the same time.

The effect of emulsifiers on SO_2 levels was examined. The result was a clear reduction of this pollutant by increasing the percentage of water in the emulsion. SO_2 levels decreased by 10.45%, 17.7% and 28% for W10, W20 and W30, respectively.

REFERENCES

[1] Fayad, M.A., Aljuwaya, T.M., Alhuzaymi, T.M., Majdi, H.S., Sultan, A.J., Chaichan, M.T., Badawy, T., Sobhi, M. (2024). Incorporating TiO_2 with oxygenated fuel and post-injection strategy in CRDI diesel engine equipped with EGR: A step towards lower NO_X, PM and enhance soot oxidation reactivity. Case Studies in Thermal Engineering, 53: 103894. https://doi.org/10.1016/j.csite.2023.103894

[2] Srinidhi, C., Channapattana, S.V., Aithal, K., Sarnobath, S., Patil, N.A., Patel, S., Karle, A., Mohammed, A.A. (2024). Relative exergy and energy analysis of DI-CI engine fueled with higher blend of Azadirachta indica biofuel with n-butanol and NiO as fuel additives. Environmental Progress & Sustainable Energy, 43(3): e14336. https://doi.org/10.1002/ep.14336

[3] Sagin, S., Karianskyi, S., Madey, V., Sagin, A., Stoliaryk, T., Tkachenko, I. (2023). Impact of biofuel on the environmental and economic performance of marine diesel engines. Journal of Marine Science and Engineering, 11(1): 120. https://doi.org/10.3390/jmse11010120

[4] Mei, Q., Naruemon, I., Liu, L., Wu, Y., Ma, X. (2023). Numerical investigation on the combustion and emission characteristics of diesel engine with flexible fuel injection. Machines, 11(1): 120. https://doi.org/10.3390/machines11010120

[5] Ning, L., Duan, Q., Chen, Z., Kou, H., Liu, B., Yang, B. Zeng, K. (2020). A comparative study on the combustion and emissions of a non-road common rail diesel engine fueled with primary alcohol fuels (methanol, ethanol, and n-butanol)/diesel dual fuel. Fuel, 266: 117034. https://doi.org/10.1016/j.fuel.2020.117034

[6] Srivatsa, C.V., Alam, S.S., Spickler, B., Depcik, C. (2024). Effect of exhaust gas recirculation on combustion characteristics of ultra-low-sulfur diesel in conventional and PPCI regimes for a high-compression-ratio engine. Energies, 17(16): 3950. https://doi.org/10.3390/en17163950

[7] Dhahad, H.A., Fayad, M.A., Chaichan, M.T., Jaber, A.A. Megaritis, T. (2021). Influence of fuel injection timing strategies on performance, combustion, emissions and particulate matter characteristics fueled with rapeseed methyl ester in modern diesel engine. Fuel, 306: 121589. https://doi.org/10.1016/j.fuel.2021.121589

[8] Aponte, J., Llano, L., Prada, V., Martinez, A. (2012). Obtaining and characterization of biodiesel water emulsion. RE&PQJ, 10(12): 1581-1584. https://doi.org/10.24084/repqj10.769

[9] Shen, S., Liu, H., Liu, Y., Liu, X., Hu, H., Hu, Z., Wang, T. (2023). Dynamic details inside water-in-oil (W/O) emulsion droplet and its impact on droplet evaporation and micro-explosion. Fuel, 338: 127254. https://doi.org/10.1016/j.fuel.2022.127254

[10] Gowrishankar, S., Krishnasamy, A. (2023). Emulsification–A promising approach to improve performance and reduce exhaust emissions of a biodiesel fuelled light-duty diesel engine. Energy, 263(Part C): 125782. https://doi.org/10.1016/j.energy.2022.125782

[11] Antonov, D.V., Fedorenko, R.M., Yanovskiy, L.S., Strizhak, P.A. (2023). Physical and mathematical models of micro-explosions: Achievements and directions of improvement. Energies, 16(16): 6034. https://doi.org/10.3390/en16166034

[12] Vellaiyan, S. (2023). Recent advancements in water emulsion fuel to explore efficient and cleaner production from various biodiesels: A retrospective review. Renewable and Sustainable Energy Reviews, 187: 113704. https://doi.org/10.1016/j.rser.2023.113704

[13] Saha, D., Sinha, A., Roy, B., Mishra, L. (2022). Effects of water-diesel emulsification on performance and emission characteristics of CI engine: A review. In Innovations in Energy, Power and Thermal Engineering: Select Proceedings of ICITFES 2020, pp. 95-107. https://doi.org/10.1007/978-981-16-4489-4_10

[14] Gautam, P.S., Vishnoi, P.K., Gupta, V.K. (2022). The effect of water emulsified diesel on combustion, performance and emission characteristics of diesel engine. Materials Today: Proceedings, 52(Part 3): 1041-1047. https://doi.org/10.1016/j.matpr.2021.10.485

[15] Park, J., Oh, J. (2022). Study on the characteristics of performance, combustion, and emissions for a diesel water emulsion fuel on a combustion visualization engine and a commercial diesel engine. Fuel, 311: 122520. https://doi.org/10.1016/j.fuel.2021.122520

[16] Gowrishankar, S., Krishnasamy, A. (2022). Novel surfactants for stable biodiesel-water emulsions to improve performance and reduce exhaust emissions of a light-duty diesel engine. Fuel, 330: 125562. https://doi.org/10.1016/j.fuel.2022.125562

[17] Hassan, Z.U., Usman, M., Asim, M., Kazim, A.H., Farooq, M., Umair, M., Imtiaz, M.U., Asim, S.S. (2021). Use of diesel and emulsified diesel in CI engine: A comparative analysis of engine characteristics. Science Progress, 104(2): 00368504211020930. https://doi.org/10.1177/00368504211020930

[18] Sartomo, A., Santoso, B., Muraza, O. (2020). Recent progress on mixing technology for water-emulsion fuel: A review. Energy Conversion and Management, 213: 112817.

https://doi.org/10.1016/j.enconman.2020.112817
[19] Abe, M. (ed.) (2004). Mixed Surfactant Systems (Vol. 124). CRC Press.
[20] Mekarun, J., Treepet, S., Rujiravanit, R., Theeramunkong, S., Watthanaphanit, A. (2024). Caffeine-containing emulsion: Influence of the HLB and mixing proportions, the oil's chemical composition, and the existence of caffeine on emulsion properties. ACS Omega, 9(2): 2113-2122. https://doi.org/10.1021/acsomega.3c03674
[21] Prabhudeva, P., Karmakar, S. (2024). Investigation on stability and energy potential of boron-loaded slurry fuel with higher loadings. Advanced Powder Technology, 35(3): 104363. https://doi.org/10.1016/j.apt.2024.104363
[22] Mondal, P.K., Mandal, B.K. (2024). Effect of fuel injection pressure on the performances of a CI engine using water-emulsified diesel (WED) as a fuel. Energy, Sustainability and Society, 14: 12. https://doi.org/10.1186/s13705-024-00442-7
[23] Keating, E.L. (2007). Applied Combustion (2nd ed.). CRC Press. https://doi.org/10.1201/9781420017489
[24] Al-Kayiem, H.H., Tukkee, A.M., See, Y.K. (2024). Experimental assessment of a solar vortex engine integrated with sensible TES at different collector configurations. Renewable Energy, 227: 120539. https://doi.org/10.1016/j.renene.2024.120539
[25] Mondal, P.K., Mandal, B.K. (2023). Optimization of water-emulsified diesel preparation and comparison of mechanical homogenization and ultrasonic dispersion methods to study CI engine performances. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45(3): 6566-6595. https://doi.org/10.1080/15567036.2019.1675811
[26] Peng, L.C., Liu, C.H., Kwan, C.C., Huang, K.F. (2010). Optimization of water-in-oil nanoemulsions by mixed surfactants. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 370(1-3): 136-142. https://doi.org/10.1016/j.colsurfa.2010.08.060
[27] Fayad, M.A. (2021). Investigation the impact of injection timing and pressure on emissions characteristics and smoke/soot emissions in diesel engine fuelling with soybean fuel. Journal of Engineering Research, 9(2): 296-307. https://doi.org/10.36909/jer.v9i2.9683
[28] Lin, C.Y., Chen, L.W. (2006). Emulsification characteristics of three-and two-phase emulsions prepared by the ultrasonic emulsification method. Fuel Processing Technology, 87(4): 309-317. https://doi.org/10.1016/j.fuproc.2005.08.014
[29] Ithnin, A.M., Noge, H., Kadir, H.A., Jazair, W. (2014). An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study. Journal of the Energy Institute, 87(4): 273-288. https://doi.org/10.1016/j.joei.2014.04.002
[30] Dhinesh, B., Bharathi, R.N., Lalvani, J.I.J., Parthasarathy, M., Annamalai, K. (2017). An experimental analysis on the influence of fuel borne additives on the single cylinder diesel engine powered by Cymbopogon flexuosus biofuel. Journal of the Energy Institute, 90(4): 634-645. https://doi.org/10.1016/j.joei.2016.04.010
[31] Khalife, E., Kazerooni, H., Mirsalim, M., Shojaei, T.R., Mohammadi, P., Salleh, A.M., Najafi, B., Tabatabaei, M. (2017). Experimental investigation of low-level water in waste-oil produced biodiesel-diesel fuel blend. Energy, 121: 331-340. https://doi.org/10.1016/j.energy.2017.01.003
[32] Ekaab, N.S., Hamza, N.H., Chaichan, M.T. (2019). Performance and emitted pollutants assessment of diesel engine fuelled with biokerosene. Case Studies in Thermal Engineering, 13: 100381. https://doi.org/10.1016/j.csite.2018.100381
[33] Sun, J., Caton, J.A., Jacobs, T.J. (2010). Oxides of nitrogen emissions from biodiesel-fuelled diesel engines. Progress in Energy and Combustion Science, 36(6): 677-695. https://doi.org/10.1016/j.pecs.2010.02.004

NOMENCLATURE

Symbols

$\dot{m}_{a,act}$	Actual air flowrate
$\dot{m}_{a,theo}$	Theoretical air flowrate
$\dot{m}_f$	Fuel mass flowrate
Q_t	Total fuel heat
V_{sn}	Swept volume per stroke

Greek symbols

ρ_{air}	Air density
ρ_f	Fuel density
η_{bth}	Brake thermal efficiency

Abbreviations

BDC	Bottom dead center
BP	Brake power
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
CA	Crank angle
D100	Pure diesel
EGT	Exhaust gas temperatures in ℃
HC	Hydrocarbons
H_2S	Hydrogen sulfide
LCV	Lower calorific value
N	Revolutions per minute
NO_X	Nitrogen oxides
PPM	Parts per million
SO_2	Sulfur dioxide
TDC	Top dead center
W10	10% water – 90% diesel emulsion
W20	20% water – 80% diesel emulsion
W30	30% water – 70% diesel emulsion