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Performance Improvement and Emissions Reduction with Environmentally Friendly Water-Diesel Emulsion Fuel

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ABSTRACT

Diesel fuel is composed of various molecules of hydrocarbons, so the properties vary from country to country. The sulfur content in Iraqi Diesel ranges from 1% to 2.5%. This abundance of sulfur contributes to a high level of emissions, including sulfur oxides, nitrogen oxides, volatile organic compounds, particulates, and carbon monoxide. To reduce emissions and improve engine performance, a diesel water mixture has been proposed as a fuel for diesel engines. This study examined the performance of a diesel engine under different operating conditions when Diesel was mixed with 10%, 20%, and 30% volume proportions of water, named W10, W20, and W30, respectively. The use of W10 and W20 caused a brake-specific fuel consumption reduction of 2.32% and 4.89%, respectively, compared to conventional Diesel, while using W30 caused an increase in brake-specific fuel consumption of about 5.75%. The brake thermal efficiency improved by 3.6% and 4.63% when using W10 and W20, respectively. While its value decreased when working with W30 by about 2.48% compared to Diesel. Working with W10 and W20 reduced engine emissions of carbon monoxide by an average of 9% and 27%, hydrocarbons by 7.8% and 20%, nitrogen oxides by 8.9% and 20.8%, and particulate matter by 4.92% and 13.1%. Operating with W10 and W20 reduced both particulate matter and nitrogen oxide emissions. The results reveal that water mixing with Iraqi Diesel is an effective means of reducing diesel engine emissions.

1. INTRODUCTION

Diesel engines play an important role in many areas, such as public transportation (buses, trains, and ships). Fuel properties vary from country to country depending on the crude oil from which it is derived, the filtering technology, and the additives included in the fuel to improve combustion quality. Construction machinery and heavy equipment are also operated with it. This fuel also generates electricity and operates water pumps that are used for agricultural purposes. Compared with other fuels, Diesel is highly thermally efficient and produces high torque. Due to the high compression ratios and high oxygen levels of this engine, it also consumes less fuel than gasoline engines [1]. In spite of their irreplaceable benefits, there has been clear concern regarding the environmental impact of these engines over the past thirty years. There are many pollutants emitted into the environment and public health from the combustion of fuel in these engines, such as nitrogen oxides, hydrocarbons, carbon dioxide, and particulates [2]. Manufacturers, researchers, and decision-makers are increasingly concerned about nitrogen oxides (NOx) and particulate matter (PM) despite the fact that carbon dioxide is a major greenhouse gas. It is challenging to reduce the combustion emissions that occur inside combustion chambers at the same time because it is very fast, complex, and often conflicting [3]. Smoke and particulate matter emissions increase when NOx reduction technologies are adopted, and vice versa [4]. The engine's performance and fuel consumption may also be negatively impacted by the technology used.

The addition of new additives to engines has been shown to improve performance and emissions in many research studies. As oxygenates (chemical compounds that contain a large amount of oxygen), ethanol and methanol have been suggested as possible additions. Because of the difference in density and viscosity between these oxygenates and Diesel, it also reduces the viscosity and density of the resulting mixture [5, 6]. Biodiesel, derived from plants or animals, has been proposed by a large group of researchers as another oxygenate. In addition to containing a high concentration of oxygen, the cetane number of this fuel is close to that of diesel fuel. The characteristics of this fuel are somewhat similar to those of Diesel. It does not require engine modifications, which makes it preferred over previous oxygenates. Many renewable resources can be used to produce this fuel, which has good engine performance. As a result of the use of biodiesel or the mixing of it with diesel fuel, emissions including HC, CO, and PM can be reduced [7]. Although this fuel offers several advantages over Diesel, it also has some disadvantages. These include a high viscosity, low calorific value, and poor stability at low temperatures. Performance is unstable due to these properties, resulting in high NOx emissions [8]. The high NOx levels are the most important factor delaying the use of biodiesel in diesel engines. Water-diesel emulsions are preferred by some researchers since the water composition contains a high amount of oxygen and hydrogen, which speeds up the oxidation process. It takes a great deal of latent heat to evaporate the water in the emulsion, and this heat is absorbed by the combustion chamber, which reduces its maximum temperature. As a result, NOx is greatly inhibited from forming. A further benefit of water evaporation from the fuel is that it can cause micro-explosions, which can reduce fuel consumption and PM emissions [9].

Diesel-water emulsion can significantly reduce the levels of NOx and PM and is one of the technical methods that researchers agree is promising [10]. Emulsifiers can reduce NOx emissions by reducing combustion chamber temperature and increasing oxygen concentration in the emulsion layer [11]. As a consequence of the partial explosion of water, PM levels are reduced, and OH radical levels are increased [12]. The study [13] showed that brake thermal efficiency is also increased under certain operating conditions.

By reducing their particle sizes, emulsions are formed by mixing initially mutually insoluble substances, such as water and oil. Over time (which is determined by several factors), the substances separate as immiscible and return to the original two-phase system. The type of mixture, viscosity, particle size, and composition of the blended materials determine how quickly the emulsion returns to the two-phase mixture [14]. However, there were significant problems preventing the application of this technology to commercial engines. The water content of diesel fuel has a very significant impact on its performance. Emulsions may also require engine modifications. When using emulsified fuel, engine performance can be improved by adjusting the injection timing [15].

Emulsified fuel was used in many experimental studies on diesel engines [16]. Higher emulsion ratios result in a longer ignition delay and longer premixed combustion period [17]. BSFC and minimum NOx are best achieved with 20-25% water in the emulsified fuel [18]. The reduction in heat losses has been shown to improve specific fuel consumption and thermal efficiency when emulsified fuel is used [19]. Using emulsified fuel with 20% water by volume gave the engine the best efficiency and emissions of NOx and soot trade-off [20].

Summing up, Iraqi diesel fuel is characterized by its high sulfur content, ranging from 1% to 2.5%. The sulfur reacts with water in the emulsion, forming sulfuric acids that corrode the fuel container or engine parts. It also produces dangerous pollutants in the exhaust, such as sulfur oxides. Iraq diesel fuel with such high sulfur content produces dangerous pollutants such as nitrogen oxides and particulate matter while increasing pollutants such as sulfur oxides, which is intolerable. The sulfur oxides in the exhaust interact with water vapor in the environment, leading to the creation of sulfur fumes that pose a great danger to humans and the environment health sustainability.

This study aims to determine diesel engine performance and pollutants emitted when the engine is run with water-diesel emulsions. The study focuses on the relationship between NOx and total suspended particulate matter, as well as emitted sulfur oxide emissions. Under varying engine load conditions and a fixed speed of 1500 rpm, water-diesel emulsions were tested in a direct injection diesel engine using traditional Iraqi diesel fuel. Emulsions were prepared by adding 10, 20, and 30 wt.% of water to conventional Iraqi Diesel. As a pre-prepared emulsion as well as running Diesel alone, engine performance and emissions parameters were measured.

2. EXPERIMENTAL SETUP

2.1 The test engine and accessories

Practical experiments were conducted using a four-cylinder diesel engine from FIAT. This four-cylinder, four-stroke engine is cooled by water and naturally aspirated. It has two valves in each cylinder, which have borne and stroke of 100 and 110mm, respectively. The engine compression ratio is 17:1, and it is equipped with a unit pump. Before taking practical measurements for all experiments, the engine is heated for no longer than 15 minutes. This is to ensure the water, lubricating oil, and combustion chamber reach steady state conditions. The number of tests was determined by conducting tests under varying engine loads at 1500 rpm. Hydraulic torque gauges (dynamometer) were used to control the engine load. Using any prepared emulsions can be applied to the engine once it has reached a stable state. Figure 1 shows a schematic diagram of the experimental setup used.

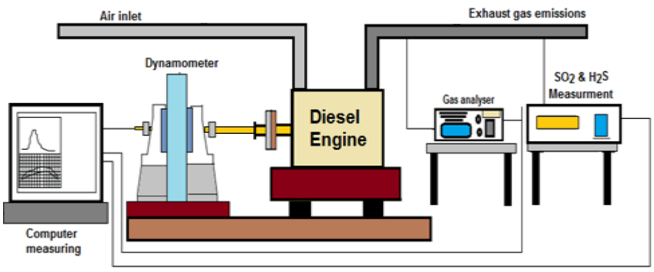

Figure 1. Schematic diagram of the used experimental setup

2.2 Measurements and instrumentations

A multigas analyzer (NOVA Model 7466 PK) was used to measure exhaust emissions such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons (HC). In order to measure the amount of SO_2 and H_2S emitted from the exhaust pipe, the G460 (German-made) was mounted in the pipe. Aerocet-USA was used to measure PM emissions. Engine noise was measured using a microphone attached to a gauge type 4615. Each blend's measured data was averaged at least three times in each condition in order to ensure high accuracy of the results.

2.3 Fuel preparation

The tests were conducted using Iraqi diesel fuel and distilled water. According to the current fuel test, Iraqi diesel fuel contains 10,000 ppm sulfur. A diesel-water emulsion. Fuel is composed of diesel fuel, water, surfactants, or surface-active agents [21] and cetane number improver. As part of the blending protocol, the cetane number improvement (type 2-ethylhexyl nitrate, also known as iso-octyl nitrate) was mixed first (1% by volume for W10, 1.5% for W20, and 2% for W30), followed by the surfactant (1% by volume for W10, 1.5% for W20, and 2% for W30) added to Diesel. The surfactants used in this study were Span 80 (Sorbitan monooleate) and Tween 80 (Polysorbate 80). When both Span 80 and Tween 80 are used together, a balance can be achieved between hydrophilic and lipophilic, helping to form stable, homogeneous diesel/water emulsions. Span 80 and Tween 80 collaborate to further stabilize emulsions by forming a protective layer around dispersed droplets, preventing droplet coalescence and re-cohesion. Surfactants offer advantages in forming stable emulsions, and resistant to diverse environmental conditions, and are suitable for various industrial and medical applications.

To ensure complete mixing between the water and Diesel, this prepared mixture is mixed by an ultrasonic shaker for approximately 90 minutes. The resulting emulsion is sampled several times, and its stability is investigated before experiments were conducted. A standard injection system was used to inject the emulsion into the engine. The properties of a diesel and water diesel emulsion can be found in Table 1.

Table 1. Iraqi diesel fuel and prepared water diesel emulsion specifications

Property	Unit	Diesel	W10	W20	W30
Density	(kg/m^3)	820	830	840	850
Cetane number		48.5	47.15	45.8	44.45
Lower heating value	(MJ/kg)	42.31	71.53	40.76	39.98
Viscosity	(cSt)	2.87	43.01	3.15	3.29
Final boiling point	(°C)	369.8	356.5	343.2	329.9
C%	(w/w)	86	80.5	75	69.5
H%	(w/w)	12.93	15.11	17.3	19.48
S%	(w/w)	1	0.821	0.642	0.463
N%	(w/w)	0.065	0.0615	0.058	0.045
O%	(w/w)	-	3.5	7	10.5
Molecular weight	(g/mole)	211	201	191	181

w/w stands for weight/weight, which is the concentration of a substance in a mixture or solution

A mixture containing 10% water and 90% diesel fuel, called W10, was prepared for testing. W20 is a mixture containing 20% water and 80% diesel fuel. W30 is the mixture, which contains 30% water and 70% diesel fuel. An emulsion formed by adding water undergoes multiple physical and chemical changes compared to Diesel. There are a number of changes that can be observed, such as a decrease in viscosity, flash blister, cetane number, enthalpy, and spill point. The changes in fuel properties result in many changes in emulsion spray evaporation characteristics, combustion process quality, and pollutants in the combustion product. The performance and emissions of engines were evaluated as a function of load. The results were obtained with a constant engine speed of 1500 rpm and a constant injection timing of 17° BTDC. Performance and research parameters calculations were based on the following set of Eqs. (1) to (8) [22]:

(1) Brake power

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

(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

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

(4) Air mass flow rate

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

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

(5) Brake specific fuel consumption

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

(6) Total fuel heat

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

(7) Brake thermal efficiency

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

2.4 Uncertainty analysis

Any measurement of any quantity is inaccurate if the measured value differs from the actual value by a specific percentage. Error levels are determined using standard calibration techniques. The process of analyzing uncertainty is known as uncertainty analysis. An uncertainty in one quantitative measurement results in uncertainty throughout an experiment. Using the equation below, the uncertainty in the results could be expressed [23]:

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

Eq. (9) is used to estimate the uncertainty of the total measurement after standard calibration for all measuring devices. The measuring devices used in the experiments and the uncertainty analysis are listed in Table 2. The measuring devices have an uncertainty of less than 5%, which is acceptable geometrically and has a high accuracy.

Table 2. Experimental measuring instruments and their uncertainties

Measuring Devices	Uncertainty (%)
Thermocouples	±0.045
Flow rate meter (Air)	±0.11
Flow rate meter (Fuel)	±0.86
Engine rpm	±0.89
Engine torque	±0.97
Emitted CO levels	±0.31
Emitted HC levels	±0.29
Emitted NOx levels	±0.47
Emitted SO_2 levels	±0.45
Emitted H_2S levels	±0.38
Noise mete	±0.62
PM concentrations	±1.13

3. RESULTS AND DISCUSSION

3.1 Emulsion stability

Oil and water emulsions are difficult because they are incompatible liquids so the product will be unstable. Mixtures can be improved by adding a small number of surfactants (surface active agents) to produce better quality and stability. The surfactant molecule consists of a hydrophobic part and a hydrophilic part. In the adsorption process, these parts must be divided so that the hydrophilic part is directed towards water and the hydrophobic part is directed towards oil. During this process, the oil absorbs water, which reduces the surface tension at the interface, reduces the free energy at the interface, and enhances the stability of the emulsion [24]. There is a synergistic effect on emulsion stability between Span 80 and Tween 80 mixtures, which are the most popular mixtures of different surfactants. The new measure of lipophilicity or hydrophilicity of a surfactant is called HLB. Water-in-oil (W/O) emulsions are produced using surfactants with a low HLB level, while oil-in-water (O/W) emulsions are produced using surfactants with a high HLB level. Typically, Span 80 and Tween 80 are used as emulsifiers in water and oil emulsions when preparing water and diesel emulsions [24]. High-HLB Tween 80 is highly oleophobic, while Low-HLB Span 80 is hydrophobic and oleophobic. Surfactants are added to emulsions in amounts ranging from 0.5% to 2% (percentage of the total volume of the emulsion). The HLB value of the surfactant mixture is calculated using the following equation:

$$HLB = \frac{(HLB_S \times W_S) + (HLB_T \times W_T)}{W_S + W_T} \tag{10}$$

Adding more water to an emulsion increases its density since Diesel has a lower density than water. Fuel viscosity and flash point are both affected by this addition. Fuels augmented with water experience an increase in density, viscosity, and flash point to varying extents. Nevertheless, with escalating temperatures within the combustion chamber, the viscosity of the emulsion declines swiftly. Adding water to Diesel maintains high engine performance since high viscosity reduces fuel injection. In order to determine the permissible amount of water to be added to Diesel, it is important to know that when the percentage of water increases above certain limits, the combustion heat is absorbed as the water changes phases from liquid to vapor, which results in heat loss [24].

An important property of emulsion is its stability, but it is also one of its problems. In the absence of compatibility between water and oil, the emulsion will separate into its basic components, and mixing will become difficult. By retaining its stability for a long time, the emulsion can be used as fuel, resulting in an improvement in engine performance and a reduction in pollution. Water, surfactant, and mixing methods all affect the stability of the emulsion. Water-diesel emulsions used in this study are shown in Table 3.

Table 3. The prepared emulsions contents and stabilities

Emulsion	Water (vol. %)	Diesel (vol. %)	CN Improver (vol. %)	Span 80 (vol. %)	Tween 80 (vol. %)	Stability (Hours)
W10	9.0	89.0	1.0	0.5	0.5	153
W20	18.5	78.5	1.5	0.75	0.75	148
W30	28	68	2	1.0	1.0	131

3.2 Engine load effect on performance

The BSFC measures the ratio between fuel consumption and energy production during a unit of time. For the tested fuel types, Figure 2 illustrates how brake fuel consumption varies with engine load. A decrease in BSFC occurs when shifting from low loads to medium loads, whereas an increase in BSFC occurs when switching from medium loads to high loads. W10 and W20 BSFC values decreased, while W30 BSFC values increased. Work with W10 resulted in a BSFC decline of about 2.32%, and work with W20 resulted in a BSFC decline of about 4.89%. In comparison to Diesel, W30 operated at a lower consumption level by about 5.75%. When dealing with diesel-water emulsions, BSFC differences are primarily caused by two factors.

To evaporate water, the latent heat of evaporation is absorbed from the combustion chamber heat. As a consequence of this process, the delay period is increased, and if no adjustment to the injection timing is made (as is the case in this study), the heat released from the combustion chamber decreases, resulting in increased fuel injection to reach 1500 rpm, increasing BSFC [25]. Secondly, adding water to Diesel causes the fuel to evaporate more quickly during delayed ignition, increasing the rate of heat release. Some droplets of these emulsions also explode in small, impactful explosions in specific areas near the nozzles and within the flame. In addition to producing faster and more efficient combustion, these explosions release heat at a greater rate because fuel and air are mixed more effectively. As the water content in the emulsion increased, the researchers observed an increase in cylinder pressure. As a result, engine power was increased, and BSFC was reduced. W10 and W20 are examples of cases where the second factor overpowers the first factor, and the BSFC decreases. When dealing with W30, the first factor overpowers the second [25]. In an emulsion with water content, the substitution of fuel with water leads to a decrease in fuel consumption. Diesel fuel has the highest BSFC at all engine loads, whereas W20 emulsion has the lowest, and these increases and decreases are not constant. There is a strong correlation between these results and those in the study [25].

In evaluating engine performance, brake thermal efficiency (BTE) is the ratio of useful work to chemical energy in the fuel. Several factors affect fuel efficiency, including density, viscosity, cetane number, etc. [26]. Added additives to Diesel or changing the Diesel can improve BTE. Water addition to Diesel has been proposed as an effective and successful additive for increasing efficiency. According to Figure 3, all loads tested resulted in high brake thermal efficiency for W10 and W20. Low and medium loads resulted in a decrease in W30 brake thermal efficiency. There was also a limited improvement at high loads only due to better heat released. Compared to Diesel, the engine operating at W10 improved brake thermal efficiency by approximately 3.6%, while the engine operating at W20 improved it by 4.63%. The W30 emulsion BTE decreased by about 2.48% compared to Diesel. The study [26] also reported similar results. Due to small explosions generating rapidly reacting hydrogen, the BTE of W10 and W20 emulsions has increased. The increased oxygen content in the combustion chamber because of these explosions improved the mixing of air and fuel. The water evaporation cooling effect decreases the temperature and pressure of the combustion chamber in the W30, affecting the BTE. As a result of this cooling effect, the delay period in the combustion chamber is lengthened, and the energy released is reduced.

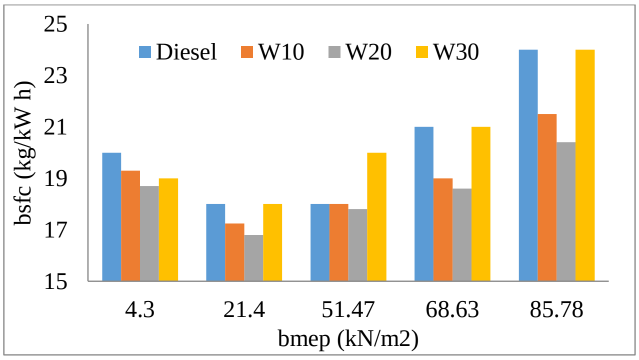

Figure 2. Load variation impact on engine BSFC for the tested fuels

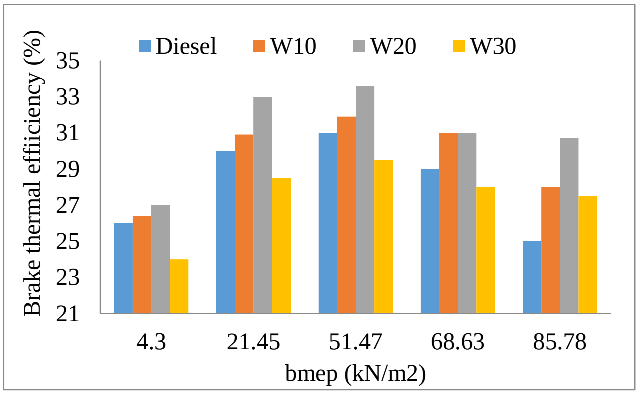

Figure 3. Load variation impact on engine brake thermal efficiency for the tested fuels

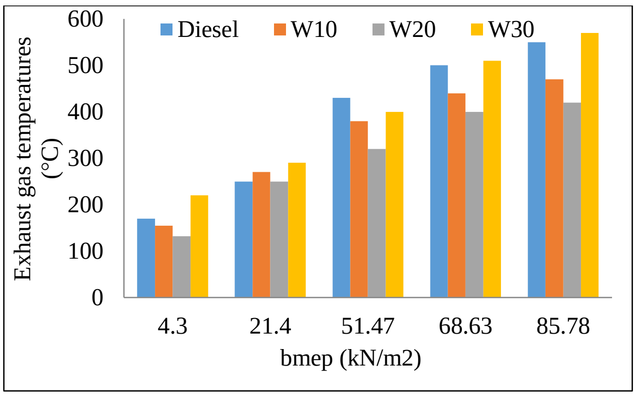

Figure 4. Load variation impact on engine exhaust gas temperature for the tested fuels

Based on the fuels tested, Figure 4 manifests the effects of changing engine load on exhaust gas temperatures (EGT). Compared to Diesel, EGT is reduced by 9.1% and 18.8% when the engine is operated at W10 and W20, respectively. It increased by 14.11 when the engine was running W30. By utilizing the heat released in the combustion chamber to produce higher temperatures in the exhaust gases, W10 and W20 emulsions have reduced EGTs. This proves that these two emulsions are suitable for diesel engines, as they improve BTE and BSFC (Figures 4 and 5). Part of the fuel in the W30 is burned during the exhaust stroke, so the engine cannot take advantage of the energy released in this stroke.

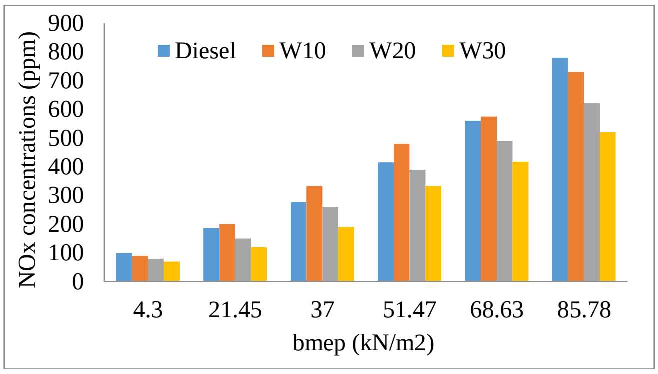

Figure 5. Load variation impact on engine emitted NOx for the tested fuels

3.3 Engine load effect on emissions

NOx is an unavoidable product from any hydrocarbon fuel combustion when three critical factors are presented: enough oxygen, a combustion temperature above 950°C, and sufficient time for formation [27]. Emulsions with a high oxygen content improve combustion and increase combustion chamber temperatures, which in turn facilitates the formation of NOx pollutants. Emulsions, on the other hand, absorb heat from the combustion chamber when water evaporates it, resulting in a reduction in temperature and hindering the formation of this pollutant [27]. The use of water in Diesel can, therefore, reduce NOx emissions.

Diesel NOx emissions can be decreased by adding water [28]. Based on the tested fuel types, Figure 5 shows how NOx emissions change with load. Engine load increases NOx levels. A greater amount of heat is released from the combustion chamber as a result of the increased amount of fuel injected. As the amount of water in the emulsion increases, NOx levels decrease. Due to the heat absorbent property of water, it reduces the temperature of the combustion chamber, thereby preventing the formation of these oxides. Compared to Diesel, engines running on W10, W20, or W30 achieved reductions of 8.9, 20.8%, and 28.78% in NOx, respectively. There was consistency between the current situation and the results of the reference [29].

In light of its harmful effects on the environment and health, it is perhaps one of the most dangerous pollutants emitted by diesel engines. When the combustion chamber gets too hot, and there is not enough oxygen, this component is emitted. PM levels in exhaust are harmful to the environment and human health. They also indicate that engines are not burning efficiently [30]. Due to the oxygen content in oxygenates (like current fuels used), the operation of oxygenates releases lower PM levels. Among the most important ways to reduce this pollution is with emulsions.

Figure 6 shows that water-diesel emulsions minimize PM emissions. Water replaces part of Diesel, which reduces sulfur levels, resulting in decreased PM levels. As sulfur concentrations drop, PM concentrations decline as well since sulfur particles act as nuclei on which carbon particles accumulate to form PM. Aerosol particles are also prevented from forming when emulsions are burned, as EGT decreases with emulsion burning. Compared to conventional diesel engines, PM levels were reduced by approximately 4.92, 13.1, and 23.2% when the engine was operated with W10, W20, and W30. With low loads, PM decreases, and with high loads, the reduction percentage increases. There is sufficient agreement between the present results and those reached by reference [31].

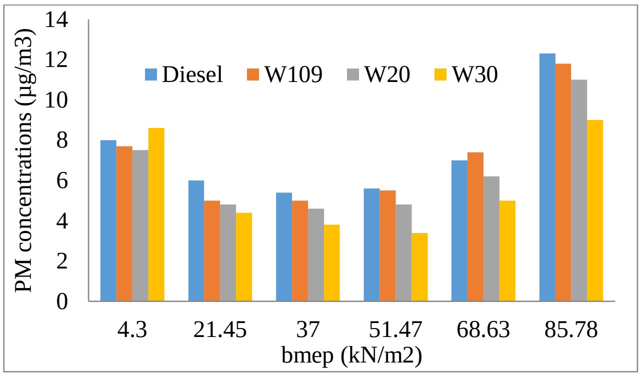

Figure 6. Load variation impact on engine emitted PM for the tested fuels

Any method used to reduce NOx will result in an increase in PM levels and vice versa, which is why researchers are interested in the trade-off between NOx and PM. Both pollutants are difficult to reduce with a single technology. Figure 7 shows how water-diesel emulsions can reduce both PM and NOx levels together. It was found that W30 reduced both pollutants the most, followed by W20 and then W10. Without modifying the engine, both W20 and W10 can be used. Alternatively, W30 can be used after adjusting the fuel injection timing to improve performance. Therefore, it is realistic that W20 will be the best emulsifier that enables low NOx and PM pollutants without modifying the engine.

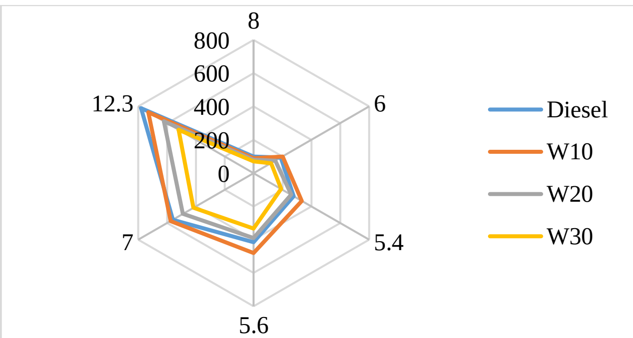

Figure 7. The PM-NOx trade-off for the tested fuels under variable engine load conditions

The exhaust gas contains hydrocarbons (HC), which are unburnt or partially burned parts of the fuel. Because diesel engines lack sufficient oxygen, levels of this pollutant are high. By having a proportion of oxygen in their composition, diesel water emulsions emit less HC than Diesel [32]. In comparison to Diesel, Figure 8 shows that the use of W10 and W20 emulsions resulted in approximately 7.8 and 20% reductions in unburned hydrocarbon levels (HC).

In the case of W30 fuel, the HC level increased by approximately 15.6%. As a result of increasing the percentage of oxygen in the combustion chamber and the temperature of the chamber, HC emissions were reduced when working with W10 and W20 fuels. HC levels increased when working with W30 due to the deterioration of combustion due to excessive cooling of the combustion chamber.

When fuel undergoes incomplete combustion within the chamber, it releases carbon monoxide (CO). With richer mixtures (higher equivalent ratios), CO concentrations rise as cylinder temperatures drop [33]. Figure 9 illustrates the fluctuation in CO emissions across various fuel types examined. As previously discussed, the utilization of emulsified fuel lowers combustion chamber temperatures under light loads, thereby restricting CO oxidation to CO_2 during low-load engine operation. Consequently, CO levels in exhaust gases are anticipated to rise.

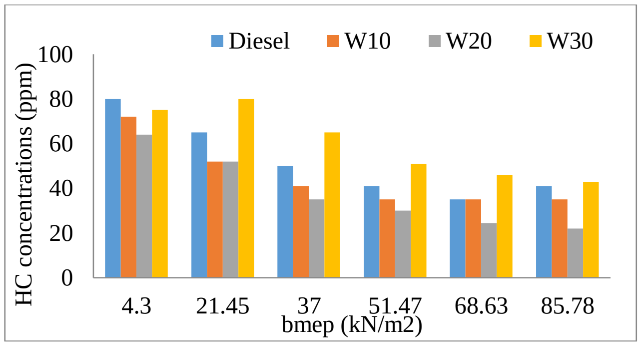

Figure 8. Load variation impact on engine emitted HC for the tested fuels

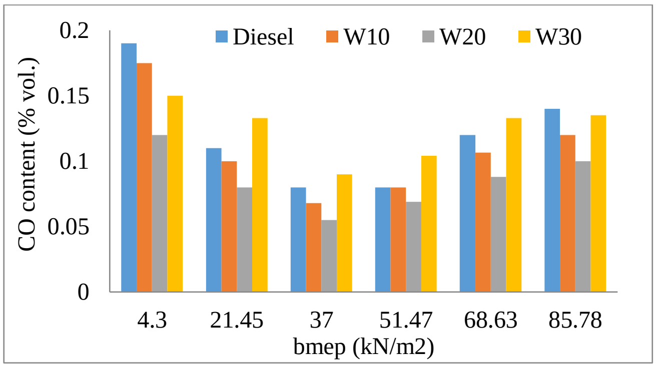

Figure 9. Load variation impact on engine emitted CO for the tested fuels

Emulsions containing elevated oxygen levels contribute to reducing these concentrations, resulting from the interplay of these factors. In high-load engines, combustion temperatures escalate, accompanied by an increase in micro-explosion occurrences, enhancing combustion efficiency and diminishing CO levels compared to diesel engines. Accordingly, CO emissions are significantly lower compared to Diesel, with W10 and W20 reducing CO levels by 9% and 27%, respectively. The findings reveal that CO concentrations decreased by no more than 13% relative to Diesel when operating with W30 instead of Diesel. These outcomes were anticipated to exhibit more pronounced reductions in CO with W30. However, due to the heightened water content in W30, the combustion chamber experiences significant cooling, compromising combustion quality and leading to elevated CO concentrations, particularly at lower engine speeds.

In the exhaust emissions of Iraqi diesel engines, concentrations of sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) can be quantified due to the sulfur content present in the fuel, approximately 10,000 ppm. When sulfur-rich fuels oxidize, they produce SO_2, as depicted in Figure 10. Despite its known health and environmental hazards, this pollutant has been largely overlooked in many literature studies due to the prevalence of ultra-low sulfur diesel fuels (ULSD), which contain sulfur content of less than 30 parts per million. The combination of SO_2 gas with water vapor, a byproduct of combustion, can generate sulfuric acid. Alongside corroding exhaust systems and contaminating catalytic converters, these acids pose significant risks to human health and the environment. Emulsions comprising Diesel and water demonstrate a proportional reduction in sulfur content with increased water content. Compared to diesel, W10, W20, and W30 formulations reduced SO_2 emissions by 11.12%, 19.56%, and 31.2%, respectively. The utilization of emulsions markedly decreases concentrations of this pollutant. Engines operating at medium loads exhibit the lowest SO_2 levels, attributed to the efficient oxidation of hydrocarbon fuels facilitated by high combustion temperatures and ample reaction time despite the ready availability of oxygen. Conversely, SO_2 levels escalate during high-load engine operation as large quantities of fuel are injected to meet performance demands.

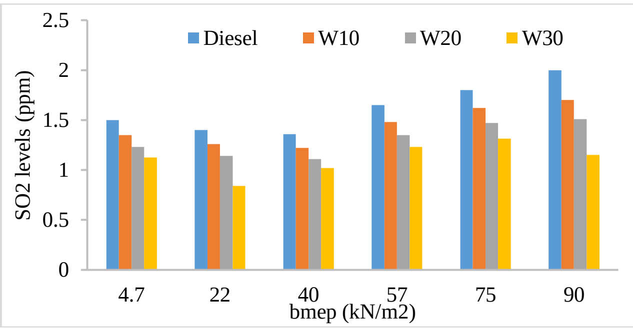

Figure 10. Load variation impact on engine emitted SO_2 for the tested fuels

Due to the sulfur content inherent in diesel fuel, exhaust gases contain concentrations of H_2S. In engines utilizing emulsions, H_2S levels decrease proportionally to the amount of added water, consequently reducing their sulfur content. Figure 11 illustrates hydrogen sulfide emissions relative to load and fuel type.

Owing to hydrogen's faster reaction rate with sulfur compared to oxygen, H_2S concentrations typically surpass SO_2 levels in exhaust emissions. Relative to Diesel, mixtures W10, W20, and W30 exhibit reductions in hydrogen sulfide emissions by 16.7%, 24.8%, and 45.7%, respectively. The utilization of water-diesel emulsions results in reductions in PM, SO_2, and H_2S concentrations. Similar findings have been corroborated by Awwad et al. [34].

As engine noise emits sound energy into the environment, it qualifies as an emission. Much like exhaust gases and particulate matter, engine noise can detrimentally affect both the environment and human health. Beyond disrupting ecosystems, impeding wildlife communication, and disturbing sleep patterns, excessive noise pollution can significantly affect human well-being. Consequently, it is imperative for diverse sectors such as automotive, aviation, and marine transportation to effectively manage and mitigate engine noise emissions. Diesel engines are known to generate considerably more noise compared to gasoline engines. Vibrations occurring within the engine block produce noise across various frequencies audible to humans. Figure 12 illustrates the engine noise measured in accordance with prior tests. Notably, W10 and W20 aqueous emulsions contributed to noise reduction by 7.36% and 10.9%, respectively. Conversely, W30 exhibited a 3.4% increase in noise, indicating a decline in combustion quality and a consequent rise in engine vibration.

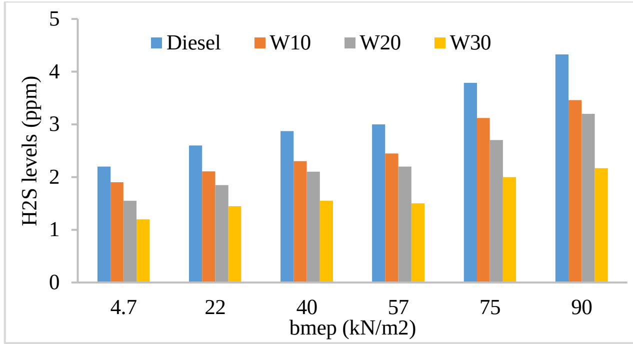

Figure 11. Load variation impact on engine emitted H_2S for the tested fuels

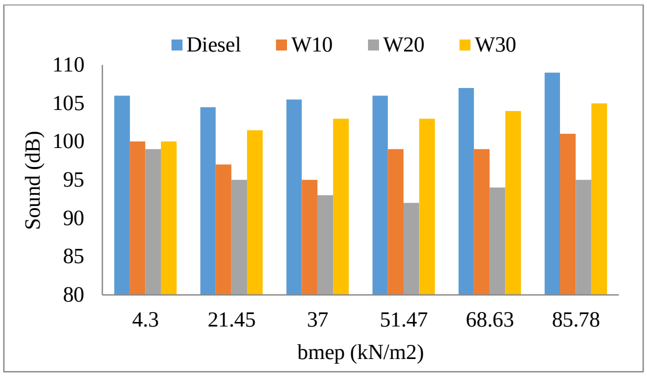

Figure 12. Load variation impact on engine noise for the tested fuels

4. CONCLUSIONS

This study endeavors to devise a method for jointly controlling NOx and PM concentrations. Experimentation was carried out utilizing a diesel-water emulsion infused with a surfactant. The fuel exhibits various favorable attributes, including its facile integration into the fuel system sans necessitating fundamental modifications. The investigation concluded that diesel engines could achieve heightened efficiency with both W10 and W20 fuels. Notably, employing W10 and W20 reduced the BSFC by 2.32% and 4.89%, respectively, compared to traditional Diesel. However, utilization of W30 led to an approximate 5.75% increase in BSFC. Moreover, W10 and W20 manifested enhancements in brake thermal efficiency by 3.6% and 4.63%, respectively, while operation with W30 exhibited a decline in this efficiency by 2.48% compared to Diesel. Across the spectrum of engine loads tested, W10 and W20 contributed to diminished engine emissions of CO, HC, NOx, and PM. Furthermore, operations with W10 and W20 concurrently abated particulate matter and NOx emissions. The noise levels across all engine loads experienced a reduction. The incorporation of a diesel-water emulsion with water additions of 20% or less demonstrated efficacy in curbing low-sulfur fuel pollutants like SO_2 and NOx. Employment of W10, W20, and W30 yielded reductions in SO_2 concentration by 11.12%, 19.56%, and 31.2%, respectively. Furthermore, the emissions of H_2S decreased by 16.7%, 24.8%, and 45.7% when the engine operated with W10, W20, and W30. Future research endeavors may explore alternative surfactant types and their implications on fuel quality, performance, and emissions.

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NOMENCLATURE

TDC	Top dead center
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CA	Crank angle
HC	Unburned hydrocarbons
HLB	The value of HLB in the surfactant blend
HLB_S	HLB value of Span 80 (HLB=4.3)
HLP_T	HLB value of Tween 80 (HLB=15)
NOx	Nitrogen oxides
PM	Particulate matters concentration in (μg/m^3)
OIT	Optimum injection timing
w_1	Filter weight before sampling operation in (g)
w_2	Filter weight after sampling operation in (g)
W_S	Weight of Span 80 in the blend
W_T	Weight of Tween 80 in the emulsion
Vt	Drawn air total volume (m^3)
Q_t	Elementary and final air-flow rate through the device (m^3/sec)
t	Sampling time in (min)
e_R	Uncertainty in the results
R	A given function of the independent variables V_1, V_2,…, V_n or $R=R(V_1, V_2, \ldots, V_n)$
$\partial R/\partial V_1$	A measure of the sensitivity of the result to a single variable