JREE: Vol. 8, No. 1, (Winter 2021) 58-68

Journal of Renewable Energy and Environment

Research Article

Journal Homepage: www.jree.ir

Assessment of the Performance and Exhaust Emission of a Diesel Engine Using Water Emulsion Fuel (WEF) in Different Engine Speed and Load Conditions

Seyed Saeed Hoseini, Mohammad Amin Sobati*

Department of Chemical, Petroleum and Gas Engineering, Iran University of Science and Technology,Tehran, Tehran, Iran.

PAPER INFO

Paper history:
Received 27 June 2020
Accepted in revised form 08 December 2020

Keywords:
Water Emulsion Fuel,
Engine Performance,
Exhaust Emission,
Engine Speed,
Engine Load

ABSTRACT

The performance characteristics and exhaust emission of a diesel engine using Water Emulsion Fuel (WEF) have been investigated under different engine speeds (1600 to 2400 rpm) and load conditions (25 to 100 %). The experiments were carried out on an air-cooled diesel engine of single cylinder using the WEF containing 5 % water, 2 % surfactant with Hydrophilic-Lipophilic Balance (HLB) of 6.8. The engine performance and exhaust emission using WEF were also compared with the Neat Diesel Fuel (NDF). According to the results, average reduction of 9.7 % in the engine torque and brake power was observed using WEF at all engine speeds. In addition, a 7.9 % increase in the Brake Specific Fuel Consumption (BSFC) and a 3.7 % increase in the Brake Thermal Efficiency (BTE) were observed for WEF in comparison with NDF in all loading conditions. In case of emission, significant lower hydrocarbon emission (i.e., 14.6 % on average) was observed for WEF comparing to NDF at all engine speeds. Moreover, a considerable reduction in the NO_x emission (i.e., 31.1 % on average) was observed for the WEF comparing to the NDF in every engine load. In summary, the application of WEF leads to the reduction in the emission of different pollutants with a positive impact on the environment.

https://doi.org/10.30501/jree.2020.233709.1115

1. INTRODUCTION

Diesel devices are broadly engaged in the industrial sectors, the agricultural applications, and the commercial transportation. Emissions from the diesel engines are a substantial source of Particulate Matters (PM) and the greenhouse gasses which in turn have negative effect on the environment. In addition, the combustion of neat diesel fuel in the diesel engines leads to the production of harmful gasses like Carbon Monoxide (CO), Nitrogen Oxides (NO_x), and Unburnt Hydrocarbon (UHC) that are categorized among the significant sources of the air pollution.

Therefore, the researchers are always looking for new fuels that can reduce the harmful emissions and enhance the engine performance. An improvement in the engine performance and exhaust emission is a substantial issue when using an alternate fuel in the diesel engine. Accordingly, the researchers have investigated the use of various fuel mixtures such as biodiesel and Water Emulsion Fuel (WEF). Gardy et al. [1] investigated the effect of different catalysts on the biodiesel production. They focused on the challenges such as corrosion and the high cost of biodiesels on the industrial scale. The advantage of WEF is its lower viscosity than the biodiesel, because high viscosity leads to the creation of disturbances in the combustion, pumping, and atomization of the diesel engine injection system. On the other hand, biofuels are more corrosive than WEF [2]. Furthermore, the application of WEF decreases the combustion enclosure temperature and, as a result, the NO_x formation in the exhaust gas. The combustion of WEF is associated with the micro explosion. In this phenomenon, the size of fuel droplets is suddenly reduced and the fuel burns with high efficiency as a result of increasing the contact surface.

Examinations of the impact of WEF on the engine performance and emission of pollutants have been studied by various researchers. Yang et al. [3] and Fahd et al. [4] stated a decrease in the brake power of WEF compared to Neat Diesel Fuel (NDF) in different engine speed conditions. In addition, according to Alenezi et al. [5], the engine power was decreased slightly using WEF compared to the NDF in the all engine load conditions. On the contrary, Seifi et al. [6] and Alahmer et al. [7] reported an opposite trend in which the brake power was higher for the WEF compared to the NDF at different engine speeds. Venu et al. [8] conducted the experimental runs on a single cylinder diesel engine using the emulsified fuel at diverse engine loads. They reported a 6.58 % increment in the Brake Thermal Efficiency (BTE) of the emulsified fuel and a 7.38 % decrement in the Brake Specific Fuel Consumption (BSFC) of the emulsified fuel in all engine load conditions. On the other hand, Ninawe et al. [9] reported the opposite conclusion. They stated the Specific Fuel Consumption (SFC) of the emulsified fuel reduced and the BTE of the emulsified increased by 7.69 % and 5.5 %,

*Corresponding Author's Email: sobati@iust.ac.ir (M.A. Sobati)
URL: http://www.jree.ir/article_120192.html

Please cite this article as: Hoseini, S.S. and Sobati, M.A., "Assessment of the performance and exhaust emission of a diesel engine using water emulsion fuel (WEF) in different engine speed and load conditions", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 8, No. 1, (2021), 58-68. (https://doi.org/10.30501/jree.2020.233709.1115).

respectively, at every engine load. Armas et al. [10] carried out experiments on a Renault F8Q 4-cylinder and turbocharged using the emulsion fuel with constant water percentage of 10 % by weight. According to their results, the brake thermal efficiency has improved slightly compared to NDF. They found that the improvement of the fuel spray atomization, as a consequence of the micro-explosion phenomenon, resulted in the enhancement of the BTE. Baskar et al. [11] examined the performance of a single cylinder air-cooled engine at different loads. They indicated the water emulsion fuel containing 10 % water with the higher BTE (i.e., 33 %) at 100 % load compared to the BTE of the NDF (i.e., 30.5 %). Lin et al. [12] investigated the performance of a water-cooled four-cylinder diesel engine using the Water in Oil (W/O) and the Oil in Water in Oil (O/W/O) emulsion fuel containing the water content of 15 % and the surfactant content of 2 % (Span 80 & Tween 80) by volume. They found that the BTE of O/W/O emulsion fuel did not differ much from the NDF, while the efficiency of W/O emulsion fuel was slightly higher than the NDF considering every load condition. Moreover, Fahd et al. [4] found that the BTE of WEF was lower than the NDF under every engine speed and load conditions due to the reduced heating value of WEF. Saravanan et al. [13] and Lin et al. [12, 14] reported the increment of the BSFC of WEF than the NDF. On the contrary, Ithnin et al. [15] and Suresh et al. [16] only considered the content of the diesel available in WEF in the calculation of BSFC and hence, they found out the BSFC reduced substantially in all operating conditions compared to the NDF. In addition, Tsukahara et al. [17] presented various reasons for the decrement of BSFC.

Generally, most of researchers [18-20] reported a reduction in the NO_x formation for the diesel-water emulsified, O/W/O emulsion fuel, and the diesel fuel with dissolved methane compared to the NDF due to the reduction of the combustion enclosure temperature. According to El Shenawy et al. [21], the emission of NO_x of the emulsion fuel was reduced by 33.6 % compared to the NDF in various engine load conditions. Fahd et al. [4] examined the CO emission of WEF containing 10 % water at different engine speeds (800-4000 rpm) at the engine loads of 10 % and 25 %, experimentally. They found that the CO emission was reduced by increment of the engine speed for both WEF and NDF. They also noted that the emission of CO was higher for the WEF than the NDF at part load. Moreover, according to Yang et al. [22], the CO emission of WEF with 10 % and 15 % water and NDF was increased by increasing the engine speed. Besides, according to their report, there was no difference between the emission of the CO using the WEF and the NDF at 100 % load. However, a slight increment in the CO emission of the WEF was observed compared to NDF in the partial load condition. They noted that the WEF had a lower combustion temperature than the NDF and hence, the CO emission was higher in the low load condition. On the contrary, according to Saravanan et al. [13] and Sudrajad et al. [23], the emission of CO was lower for the WEF than the NDF. They concluded that the micro-explosion phenomenon led to the production of richer air-fuel mixture and as a consequence of enhanced combustion, the CO formation was reduced. Yang et al. [22] reported that the HC emission using the WEF did not differ much from the NDF in the full-load condition. However, a slightly higher HC emission was reported using the WEF than the NDF in the partial-load condition. They concluded that the evaporation of the contained water in the WEF resulted in a decrease in the temperature of the combustion enclosure and led to incomplete combustion, which in turn increasd the HC emission for the WEF compared to the NDF. Kannan et al. [24] pointed out that the emission of HC was lower for the WEF than the NDF in different load conditions. They reported 26.5 % and 42.5 % decrements in the emission of HC for the WEF with the water content of 10 % and 20 %, respectively. They mentioned that the micro-explosion phenomenon resulted in the enhanced fuel combustion and the improvement of the air-fuel mixing. On the contrary, Subramanian [25] reported that the HC emission was higher using the WEF instead of NDF in the all load conditions.

Table 1 summarizes the different researches considering the engine performance and exhaust emission using WEF. Moreover, the effect of using diverse additives in the WEFs on the engine performance and exhaust emission can be observed in other works [26-28].

Based on the literature review, WEF is an efficient fuel that can improve the diesel engine performance and reduce the harmful exhaust emission. Nevertheless, contradictory results regarding the engine performance and exhaust emission can be figured out in the work of researchers. In our previous paper, the optimized formulation of the water in diesel emulsion fuels was found considering different criteria including fuel stability, engine performance, and emission at a constant engine speed under the full-load condition [29]. In continuation of our first paper, the principal goal of this investigation is to examine the performance and exhaust emission of a diesel engine considering the optimized WEF under different engine speed and load conditions. Therefore, the effects of engine speed and load on the performance and emission characteristics of the diesel engine were investigated using the optimized formulation of the WEF. In addition, the engine performance and exhaust emission using the WEF were compared with the NDF in detail.

2. EXPERIMENTAL DETAIL

2.1. Materials

In the present investigation, the NDF was supplied from the domestic fuel station in Tehran, Iran. The specifications of NDF are indicated in Table 2. It should be noted that the application of surfactant as the emulsifier is essential for the emulsion formation using two immiscible liquids of water and diesel. Therefore, a blend of two surfactants of Span 80 (hydrophobic) and Tween 80 (hydrophilic) supplied from Merck company (Germany) was used. More details regarding the specifications of the surfactant mixture and the stability of the prepared emulsion fuel can be found elsewhere [29].

2.2. The procedure of preparation of water emulsion fuel (WEF)

A 400 W ultrasonic transducer equipped with a titanium horn with 12 mm diameter and constant frequency of 20 kHz was employed in the procedure of the WEF preparation. Based on our previous paper, the best formulation for the WEF was considered with the water content of 5 %, the surfactant content of 2 %, and Hydrophilic-Lipophilic Balance (HLB) of 6.8 [29]. In order to produce the emulsion fuel, the required amount of distilled water was introduced into the cylindrical container at first and a defined amount of Tween 80 was added gradually. Then, the power of 300 W was adjusted for the ultrasound apparatus. The immersion depth of the probe was selected as 1 cm. Next, the distilled water and Tween 80 were mixed under ultrasound irradiation for 10 min. Afterwards, a desired amount of Span 80 and the neat diesel was incorporated to the solution under the ultrasound irradiation for 10 min. It should be noted that the HLB of the surfactant mixture was calculated by Eq. (1):

$$\mathrm{HLB} = x_1 \times H_1 + x_2 \times H_2 \tag{1}$$

H_1 and H_2 are the HLB of Span 80 and Tween 80, respectively. In addition, x_1 and x_2 are the mass fraction of each surfactant in the WEFs [34]. Furthermore, it should be added that the stability of the produced WEF was about 17 days.

Table 1. Highlights of the results of researchers on the performance and exhaust emission using the WEF

Scholar's name	Engine type & fuel composition characteristics	Performance characteristics	Emission characteristics
Yang et al. [3]	Toyota 4-cylinder Water content of 5 % by volume, organic additive, and NP-9 surfactant percentage of 12.6 % by volume	The brake power was lower than water emulsion fuel at full-load engine, while BTE was higher at all speeds.	Decrement of NO_x emission using WEF in all speed conditions and a remarkable reduction observed at higher engine speed. No considerable difference between CO and HC emission of WEF and NDF.
Attia et al. [30]	3-cylinder and turbocharged engine Water content of 17 % by volume and emulsifier content of 0.5 % by volume (span 80 and tween 60)	A 20 % increment in the BTE of WEF than NDF	The HC, NO_x and smoke emissions decreased up to 35 %, 25 %, and 80 % for WEF instead of used NDF, respectively. The reduction of emission characteristics increased for over engine load of 75 %.
Ghojel et al. [31]	4-cylinder and direct injection engine at an engine speed of 2200 and an engine load of 150 N.m Water content of 13 % by volume	The power output was lower and the BSFC was higher for WEF than the NDF.	90 % and 37 % reductions in HC and NO_x emission of WEF compared to NDF, respectively.
Badrana et al. [32]	A single-cylinder and direct injection engine Different water contents (10 %, 15 %, 20 %, 25 %, and 30 % by volume)	The torque, power, and BTE increased by increasing the engine speed, while the BSFC reduced slightly for both WEF and NDF. The torque and power of WEF were slightly higher than NDF; plus, the BTE and BSFC were significantly more for WEF.	The NO_x and PM emission reduced by using WEF.
Nadeem et al. [33]	A water-cooled and four-cylinder diesel engine Water contents of 5 %, 10 %, and 15 % by volume	The torque and power were lower for WEF than the NDF, while the BSFC was greater for WEF.	The NO_x and CO emission augmented with increment of engine speed for both WEF and NDF. The NO_x, CO and PM emission of WEF decreased compared to the NDF.

Table 2. NDF specifications

Specification	Value	Unit	Test type
Net Calorific value	46.42	MJ/kg	ASTM D 4868
Density at 15 °C	0.827	g/cm^3	ASTM D 1298
Kinematic viscosity at 40 °C	2.83	mm^2/s	ASTM D 445
Flash point	67	°C	ASTM D 93
Pour point	-6	°C	ASTM D 2500
Cloud point	1	°C	ASTM D 97
Cetane number	56.34	----	ASTM D 976
Sulfur content	48	ppmw	ASTM D 4294
Water content	54	ppmw	ASTM D 6304

2.3. Diesel engine experimental set-up

In the current study, the engine experiments were accomplished to examine the engine performance and exhaust emission in the various different speed and load conditions using the WEF and NDF. The detailed properties of single single-cylinder air-cooled diesel engine are summarized in Table 3. It is necessary to mention that the Eddy current type DC dynamometer (±0.1 kW precision for power value, ±0.1 Nm precision for torque value, and ±1 rpm precision for rotational speed value) was connected to the diesel engine. The controlled values in these experiments were the applied load on the dynamometer applied to the engine, the engine speed, and the fuel type.

Table 3. Engine specifications

Type	Lombardini-Diesel 3LD510
Stroke	90 mm
Number of cylinders	1
Compression ratio	17.5:1
Swept volume	510 cc
Bore	85 mm
Maximum power at 3000 rpm	9 kw
Maximum torque at 1800 rpm	32.8 Nm

The stages of testing are as follows:

- Setting up the dynamometer: the central control system was turned on by the main switch. Then, the dynamometer and all measuring devices were started up.
- Setting up the emission analyzer: the emission analyzer apparatus was turned on using the software. It became ready to carry out the test after testing the leakage of the hose.
- Turning on the engine: the engine was operated through by pushing the start key in the software. It should be noted that the engine was ready for the test by reaching to the steady state condition after about 15 min.
- Appling the engine speed and load: there were two modes for each of the tested fuel (i.e., the WEF and the NDF). In the first mode, different engine speeds were examined in the extent of 1600 to 2400 rpm under the full full-load condition. In the second mode, the different engine loads were examined in the range of 25 to 100 % at the fixed engine speed of 1800 rpm.
- Measurement of torque, power, and specific fuel consumption: These items were measured using an eddy current dynamometer automatically. The related data was were saved in a file on a computer.
- Calculation of the brake power, the BSFC, and the BTE: the values of these items were calculated using the equations listed in Table 4.
- Measurement of emission of different pollutants: the sensor was employed at the end of exhaust pipe. Then, the quantity of different pollutants was displayed on the monitor in at the variousdifferent engine speeds and loads. The data was recorded after a few seconds to reach the a steady conditionsstate. At the end of each test, the sensor was removed from the smoke path to clean any possible deposit. This action increases the accuracy of the measurement.

It should be noted that the evaluation of effective parameters of exhaust emissions such as NO_x, HC, CO, and CO_2 was determined by AVL DITEST GAS 1000 emission analyzer [35]. The properties of the applied emission analyzer are indicated given in Table 5. The data of emission of the pollutants was recorded via special software and Bluetooth that were mounted on the computer system. Moreover, the calorific heat value was determined through Gallenkamp bomb calorimeter having precision of ±0.1 %. The arrangement of engine test set up is illustrated in Figure 1.

It should be noted that the experimental runs were carried out three times with the relative standard deviation between 1-3 %.

Table 4. Engine performance parameters

Engine performance characteristics	Equation	Equation No.	Explanation
Brake power (kw)	$P_b = \frac{2\pi TN}{60000}$ [36]	(2)	T = torque (Nm) N = engine speed (rpm)
Specific fuel consumption (gr/kwh)	$SFC = \frac{M_f}{P}$ [36]	(3)	Mf = mass flow rate (gr/h) P = power (kw)
Brake specific fuel consumption (gr/kwh)	$BSFC = \frac{M_f}{P_b}$ [36]	(4)	Mf = mass flow rate (gr/h) Pb = brake power (kw)
Brake thermal efficiency (%)	$BTE = \frac{3600}{H_v \times BSFC} \times 100$ [36]	(5)	Hv = calorific heat value (MJ/kg) BSFC = brake specific fuel consumption (gr/kwh)

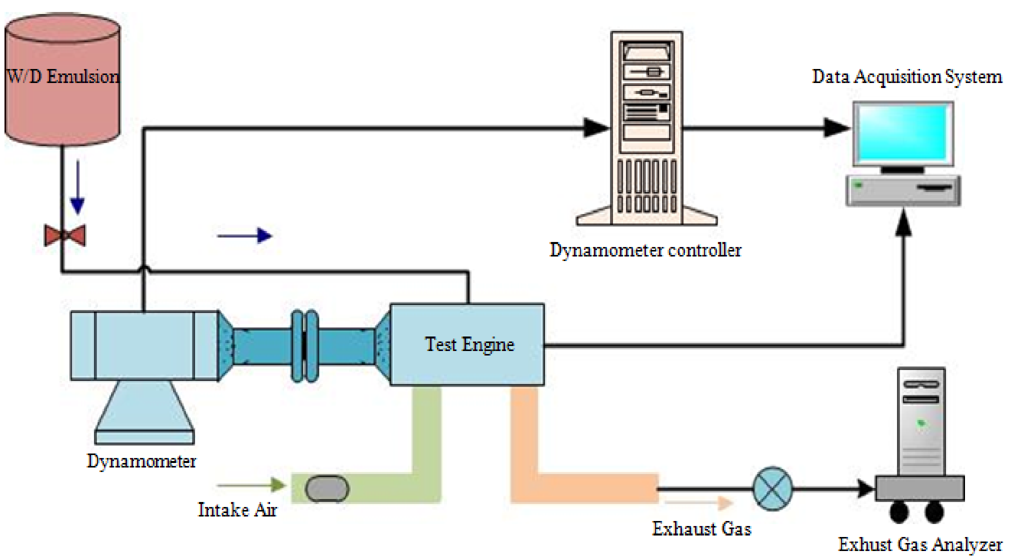

Figure 1. Schematic of the experimental set up used in the engine test

Table 5. Specifications of AVL DITEST GAS 1000 emission analyzer

Parameter	Evaluation extent	Evaluation precision
NO_x	0-5000 ppm vol	1 ppm vol
HC	0-3000 ppm vol	1 ppm vol
CO	0-15 % vol	0.01 % vol
CO_2	0-20 % vol	0.01 % vol

3. RESULTS AND DISCUSSION

In order to investigate the impact of the engine load, several experimental runs were accomplished at different engine loads (25 to 100 % with 25 % increment) at a constant engine speed of 1800 rpm for the WEF and NDF. Furthermore, several experimental runs were performed at different engine speeds (1600 to 2400 rpm with 200 rpm increment) under full load for the WEF and NDF. It should be mentioned that the formulation of the WEF was optimized in our previous study using response surface methodology considering performance parameters and emission [29]. The RSM suggested that the appropriate formulation for the WEF was water content of 5 %, surfactant content of 2 %, and HLB of 6.8. The same formulation is selected in the current investigation for the WEF.

3.1. Impact of the engine speed and load on the torque

The values of the engine torque for the WEF and NDF are compared in Figure 2 in the different engine speed and the load conditions. According to Figure 2, the engine torque increases with the decrement of the engine speed and the increment of the engine load. The reason for the lower values of the torque at a high speed is that the engine does not have enough capability of ingesting the entire charge of air. The high values of the torque at the high loads can be ascribed to the reduction of the frictional losses [37]. At all speeds and loads of the engine, the WEF has the lower values of torque compared to the NDF because of the existence of water in the WEF. Generally, the average decrement in the values of the torque for the WEF, compared to the NDF, was 9.7 % and 13.4 % at different speeds and loads in the examined range, respectively. Researchers found that the high value of the required energy for the water vaporization, which is greater than 10 times than the diesel vaporization, led to lower values of the engine torque for the emulsion fuels [3, 4, 30, 38]. Calorific value of the examined WEF was 41.12 MJ/kg and the calorific value of NDF was 46.42 MJ/kg. Accordingly, the reduction of the calorific value of the WEF resulted in the lower values for the engine torque.

3.2. Impact of the engine speed and load on the brake power

The values of the engine brake power for the WEF and NDF are compared in Figure 3 at different engine speeds and loads. According to Figure 3, the brake power raises with the increment of the engine speed and the load condition. Besides, the values of the brake power are lower for the WEF compared to the NDF. Generally, the average decrease in the brake power of the WEF compared to the NDF was 9.7 % and 11.3 % at different speeds and loads in the examined range, respectively. This is because of the increment of the power stroke per unit time by the increment of the engine speed as well as the decrement of the friction losses with the rise of engine load [6]. According to the existence of the water in the WEF, the brake power for the WEF is lower than the NDF. The decrement of the brake power using the WEF compared to the NDF was also reported elsewhere [3, 4, 39]. Moreover, it should be mentioned that the lower calorific value of the WEF in turn decreased the brake power. From another perspective, the increment of the maximum pressure and the ignition delay increased the pressure before the top dead center. As a result, the compression work increased which in turn reduced the power output of the engine [38, 40].

3.3. Impact of the engine speed and load on the BSFC

Figure 4a shows the BSFC values for the WEF and NDF at different engine speeds. As can be observed, increasing the engine speed up to a certain value leads to a decrease in the BSFC. The further increment of the engine speed beyond the mentioned limit leads to an increment in the BSFC. It should be considered that at lower speeds, the loss of the heat from the combustion enclosure walls is higher and the thermal efficiency is lower; as a consequence, more fuel is burned in the engine for power generation. Note that at high speeds, the fuel consumption increases to some extent due to an increment in the frictional power in the engine. The values of the BSFC are higher for the WEF than the NDF at different engine speeds and loads. Generally, the average increase in the values of BSFC for the WEF compared to the NDF was 8 % and 7.9 % at different speeds and loads in the examined range, respectively. In fact, considering the same volume of fuel, there is a lower amount of diesel in the WEF than neat diesel [3, 37, 41]. The BSFC values of the WEF and NDF are compared at different engine loads in Figure 4b. As can be observed, the BSFC is reduced by an increment in the engine load. It should be mentioned that the engine consumes the fuel with better efficiency at high load and hence, the fuel consumption decreases [15, 42].

3.4. Impact of the engine speed and the load on BTE

Figure 5a shows the values of the BTE for the WEF and NDF at different engine speeds. As can be observed, the BTE raises with the increment of the engine speed until it attains its highest value and then, decreases. At low speeds, the larger time is available for the heat transfer to the cylinder, which in turn results in the higher heat loss. The BTE decreases at higher speeds according to the increment of the frictional power of the engine, which is followed by more fuel consumption. In addition, the BTE of the WEF is greater than the NDF at different engine speeds. The micro-explosion phenomenon causes large droplets of the WEF to convert into small droplets, which accelerate the process of vaporization of the fuel and improve the mixing of the fuel with air, which leads to better combustion and thermal efficiency increment. Moreover, the existence of the water droplets in the WEF results in the decrement of the calorific value of the fuel and the subsequent increment of BTE [3, 37, 41]. Figure 5b compares the BTE values for the WEF and NDF at different engine loads. As can be seen, the BTE increases by an increment in the engine load due to the decrement of friction losses and increment of the brake power. Furthermore, the values of BTE for the WEF are higher than the NDF in all load conditions [15, 42]. Generally, the average increase in the values of BTE for the WEF compared to the NDF was 3.6 % and 3.7 % at different speeds and loads in the examined range, respectively.

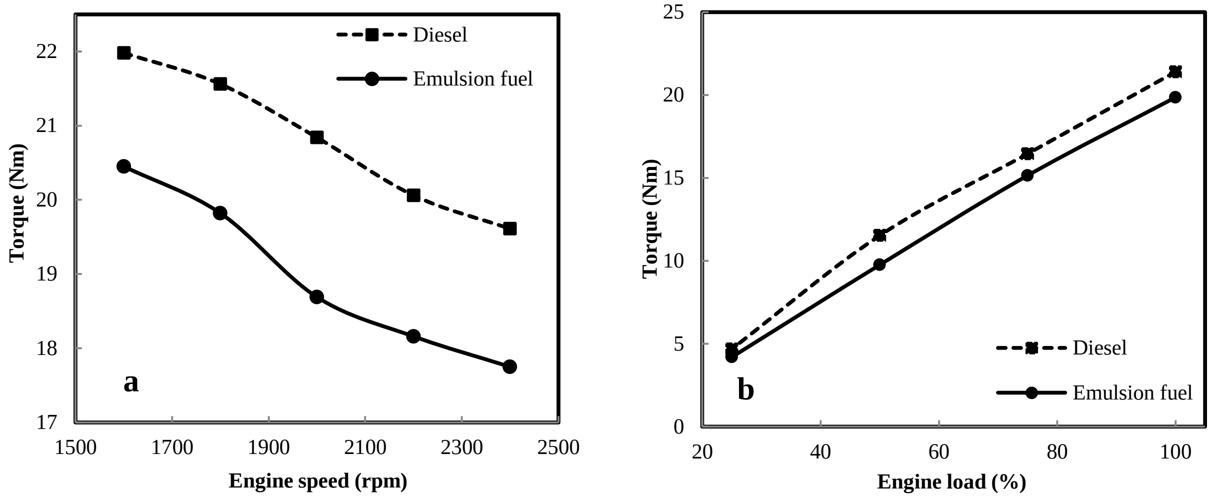

Figure 2. Comparison of the engine torque using the emulsion fuel and neat diesel fuel (a) in different speeds and full load condition, (b) in different loads and engine speed of 1800 rpm

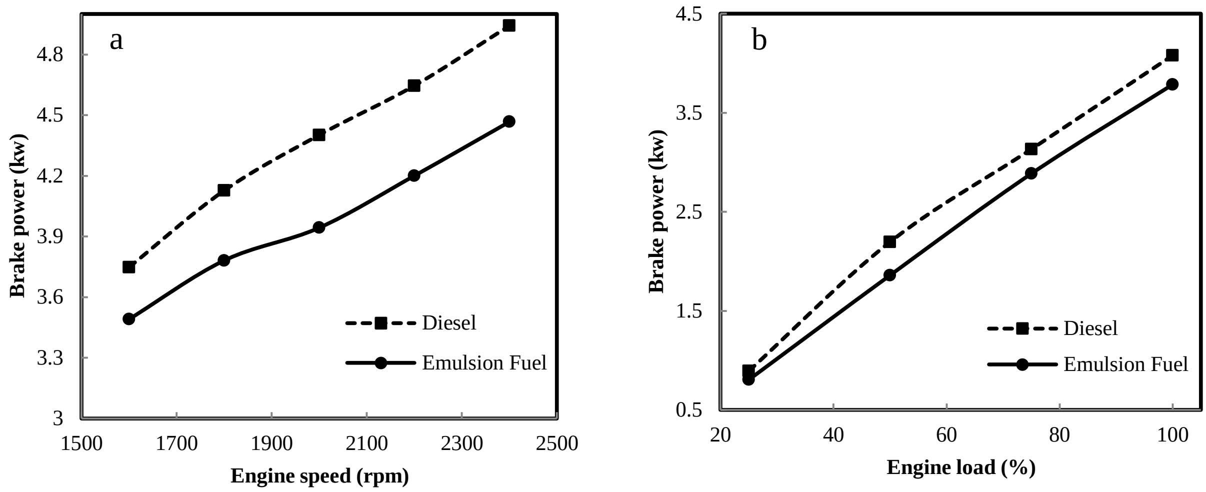

Figure 3. Comparison of the brake power using the emulsion fuel and neat diesel fuel (a) in different speeds and full load, (b) in different loads and engine speed of 1800 rpm

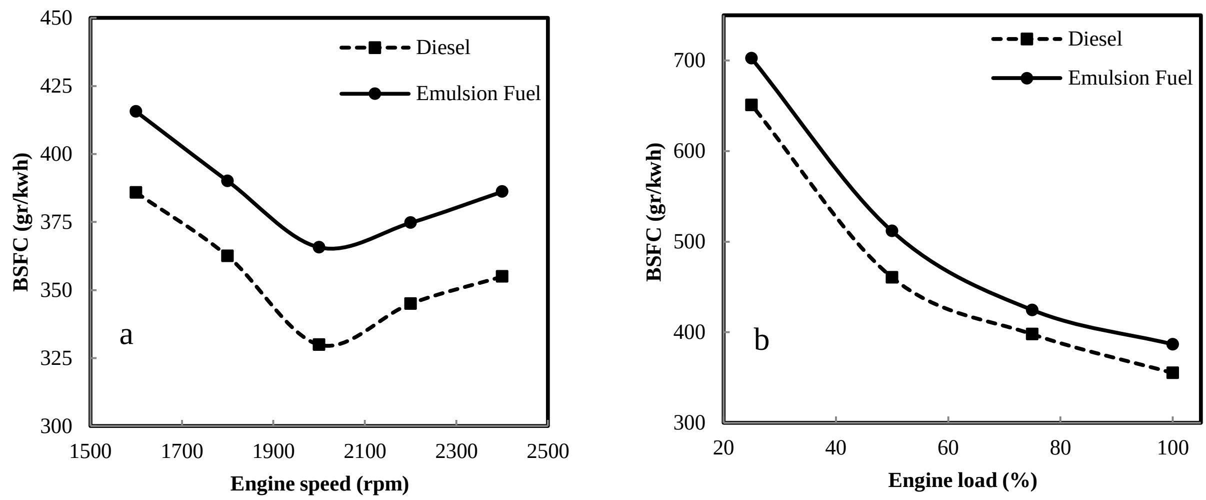

Figure 4. Comparison of BSFC using the emulsion fuel and neat diesel fuel (a) in different speeds and full load condition, (b) in different loads and engine speed of 1800 rpm

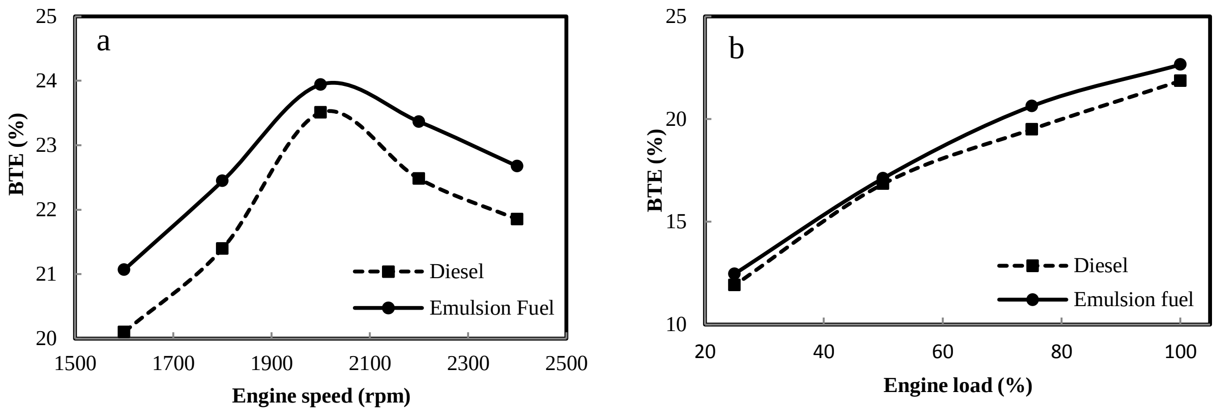

Figure 5. Comparison of BTE using the emulsion fuel and neat diesel fuel (a) in different speeds and full load condition, (b) in different loads and engine speed of 1800 rpm

3.5. Impact of the engine speed and the load on CO emission

Figure 6 illustrates the CO emission of the WEF and NDF at different engine speeds and loads.

As can be seen in Figure 6a, the increment of the engine speed results in the increase in the CO emission. It should be noted that the increment of the engine speed results in a decrement in the combustion time, which in turns increases the CO emission due to incomplete combustion [33].

In addition, according to Figure 6a, CO emission of the WEF is higher than the NDF at lower engine speeds, and vice versa. It should be noted that the process of mixing air-fuel is under the influence of the difficulties of the atomization of the WEF as a result of its greater viscosity than the NDF. This effect is more pronounced at lower speeds. It should be mentioned that the viscosity of the NDF and the WEF at 40 °C is 2.83 mm^2/s and 3.75 mm^2/s, respectively. As a result, the WEF has higher viscosity than the NDF, which could be the reason for the emission of more CO using the WEF than the NDF in lower engine speed conditions. Besides, the micro explosion phenomenon occurs very well at the higher engine speeds and the combustion is improved [3, 33, 43]. Figure 6b demonstrates the CO emission for the WEF and the NDF at different engine loads. As observed earlier, CO emission is increased by an increase in the engine load. This can be attributed to incomplete combustion of the sprayed excess fuel and the production of richer fuel-air mixture at high engine loads [42]. The CO production is increased as a result of the shortage of oxygen in the combustion environment [44]. As can be seen in Figure 6b, the emission of CO of the WEF is higher than the NDF at 100 % load, whereas the CO emission for the WEF is lower at the other engine loads. The similar trend was also reported elsewhere [42, 45]. It should be mentioned that the increment of the engine load resulted in the consumption of more fuel and the subsequent increase in the inside temperature of the cylinder. For the WEF, a significant amount of heat is consumed for the phase change of water to steam which decreases the temperature and ultimately leads to the higher emission of CO for the WEF than the NDF at 100 % engine load [46].

3.6. Impact of the engine speed and load on the HC emission

Figure 7a depicts the HC emission for the WEF and the NDF at different engine speeds. It should be noted that the value of HC emission increases by an increment in the engine speed. The increment of the HC emission can be ascribed to the production of richer fuel-air mixture at the high engine speeds. As can be observed in Figure 7a, the emission of HC for the WEF is lower than the NDF at all engine speeds. This can be attributed to the micro-explosion and more complete combustion of the emulsion fuels [47], and the generation of the OH radical from the water in the emulsion fuel, which favors complete combustion [24]. In general, the average decrease in emission of HC using the WEF compared to the NDF was 14.6 % considering different speeds in the examined range.

Figure 7b illustrates the HC emission for the WEF and NDF at different engine loads. The observed trend can be ascribed to the fact that non-uniformity of the fuel-air blend causes the lack of adequate oxygen for complete consumption, which in turn leads to higher HC emission [42].

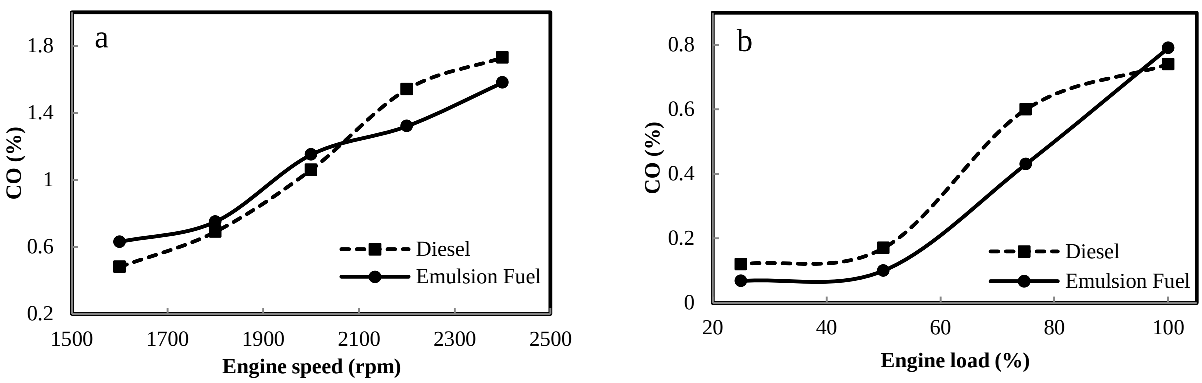

Figure 6. Comparison of CO emission using the emulsion fuel and neat diesel fuel (a) in different speeds and full load condition, (b) in different loads and engine speed of 1800 rpm

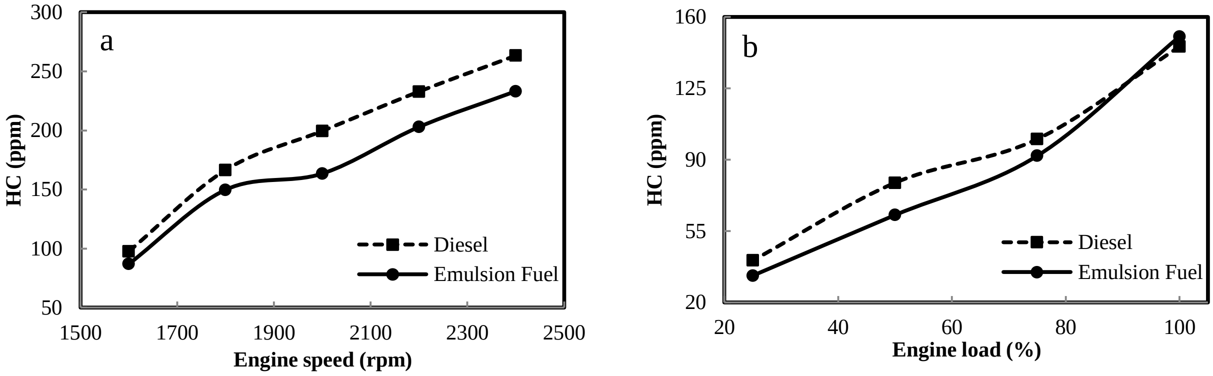

Figure 7. Comparison of HC emission using the emulsion fuel and neat diesel fuel (a) in different speeds and full load condition, (b) in different loads and engine speed of 1800 rpm

3.7. Impact of engine speed and load on CO_2 emission

Figure 8a depicts CO_2 emission for the WEF and the NDF at different engine speeds. As can be seen, the CO_2 emission is increased by the increment of the engine speed. It should be noted that as the engine speed increases, more fuel is consumed and thus, the blending of air and the atomized fuel is improved, which in turn increases the emission of CO_2 [43]. Moreover, the WEF emits higher CO_2 than the NDF at every speed. Generally, the average increment in the emission of CO_2 for the WEF than the NDF was 5.5 % considering the different speeds in the examined range. It can be argued that the increment of CO_2 emission implies more complete combustion. It can be also explained that the generated steam from the emulsion fuel causes the formation of OH radical during the combustion process that collaborates to combine oxygen with CO and hence, the emission of CO_2 increases [37]. Figure 8b shows CO_2 emission for the WEF and the NDF at different engine loads. Generally, the emitted CO_2 is increased as the engine load is increased. Higher fuel consumption and the existence of the sufficient oxygen, especially for the emulsion fuel, are two reasons for significant emission of CO_2 at high loads. Furthermore, a decrement in the equivalence ratio and an increment in the fuel-rich combustion have caused more fuel to mix with air which in turn increases the CO_2 emission [12]. On the other hand, at higher temperatures, the combustion is more complete and hence, the emission of CO_2 increases [42, 44]. As can be observed in Figure 8b, generally, the WEF emits higher CO_2 than the NDF at different engine loads, especially at higher loads. This can be ascribed to more oxygen in the WEF combustion which is the main factor for higher CO_2 emission than the NDF [15, 37, 39].

3.8. Impact of the engine speed and load on the NO_x emission

Figure 9a shows NO_x emission for the WEF and the NDF at different engine speeds. It should be noted that NO_x emission increases as the engine speed raises. This is because of the fact that the increment of the gas temperature results in the conversion of elemental nitrogen of air to NO and hence, NO can easily merge with O_2 to produce NO_2 [12, 33]. As can be observed in Figure 9a, the emission of NO_x for the WEF is lower than the NDF. In general, the average decrease in the NO_x emission for the WEF than the NDF was 14.7 % considering different speeds in the examined range. It can be mentioned that the NO_x emission is influenced by the combustion temperature directly. The evaporation of water in the WEF results in a decrement in the combustion temperature, which leads to a reduction in the NO_x formation. A strong relationship between the reduction of NO_x emission and the increment of water percentage in the emulsion fuel was reported elsewhere [3, 37]. Figure 9b illustrates NO_x emission for the WEF and the NDF at various engine loads. According to Figure 9b, by an increment in the engine load, the emission of NO_x increases until it attains its highest value and then decreases. This trend was also reported elsewhere [42]. On the one hand, the increment of the combustion enclosure temperature and the enhancement of the cylinder pressure as a result of the increment of the engine load can be a factor in the increment of NO_x emission. On the other hand, a richer mixture of fuel-air and the deficiency of oxygen at full load cause a decrease in the NO_x emission [4]. Furthermore, the emission of NO_x is lower for the WEF than NDF at different loads. Generally, the average decrease in the NO_x emission for the WEF than the NDF was 31.1 % considering the different loads in the examined range.

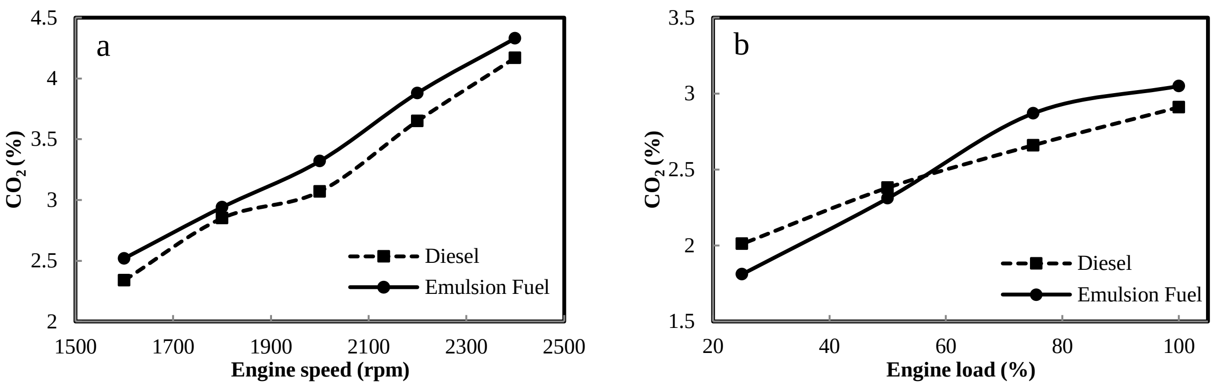

Figure 8. Comparison of CO_2 emission using the emulsion fuel and neat diesel fuel (a) in different speeds and full load condition, (b) in different loads and engine speed of 1800 rpm

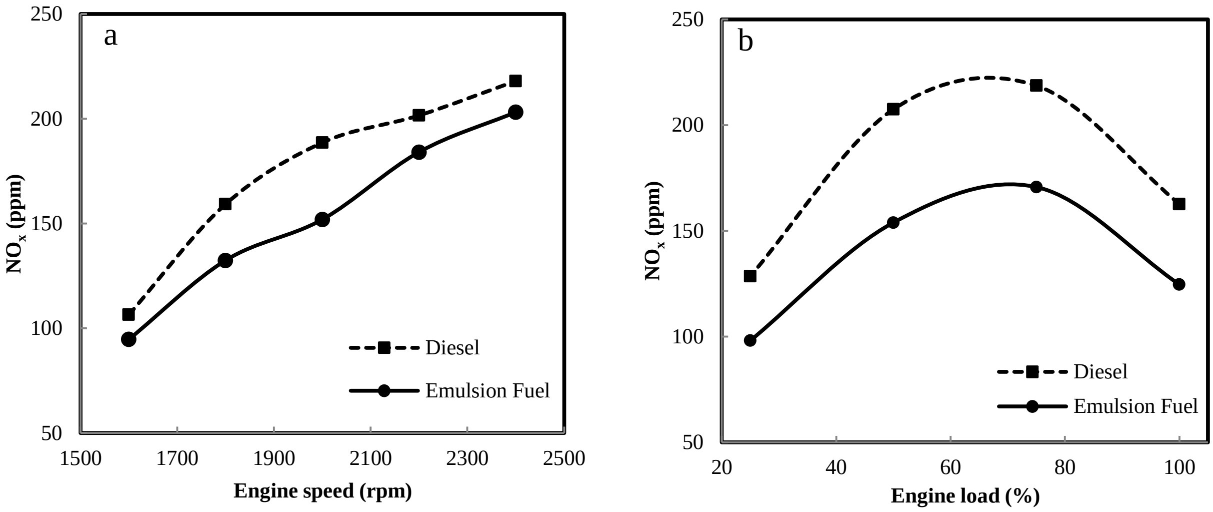

Figure 9. Comparison of NO_x emission using the emulsion fuel and neat diesel fuel (a) in different speeds and full load, (b) in different loads and engine speed of 1800 rpm

4. CONCLUSIONS

In the current study, a blend of diesel, water, and surfactant (combination of 80 and span 80) was applied to generate WEF. The best formulation of the water emulsion fuel based on our previous study was considered with 5 % of water content, 2 % of surfactant content, and HLB of 6.8 for the surfactant. The engine performance and exhaust emission of the WEF examined in the aforementioned conditions and the NDF was compared under different engine speed and load conditions. The main results are as follows:

- The engine torque and brake power were lower for the WEF than NDF in engine speed and load conditions. This can be ascribed to the lower calorific value of the WEF than the NDF due to the existence of water in the WEF.
- The values of BSFC and BTE of the WEF were higher than the NDF. In case of the BSFC, the lower content of diesel in the WEF results in the higher fuel consumption of WEF than the NDF. The phenomenon of micro-explosion in the combustion of WEF has a substantial role in the improvement of the combustion which increases the BTE.
- Significant lower HC formation was observed for the WEF than the NDF. The existence of water in the WEF results in the production of OH radical, which is an essential cause of the decrement of the HC concentration of the WEF compared to NDF.
- The emission of NO_x was reduced considerably for the WEF compared to the NDF in the engine speed and load condition. This is directly associated to the decrement of the combustion temperature due to the existence of water in the WEF.

As a consequence, it should be mentioned that the application the water emulsion fuel instead of petro-diesel leads to a substantial decrement of the emission of some important pollutants such as HC and NO_x.

5. ACKNOWLEDGEMENT

The authors would like to thank the Renewable Energy Institute of Tarbiat Modares University for their supports in the engine tests.

NOMENCLATURE

WEF	Water emulsion fuel
NDF	Neat diesel fuel
HLB	Hydrophilic-lipophilic balance
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
HC	Hydrocarbon
CO_2	Carbon dioxide
NO_x	Nitrogen oxide
RPM	Revolution per minute

REFERENCES

1. Gardy, J., Rehan, M., Hassanpour, A., Lai, X. and Nizami, A.S., "Advances in nano-catalysts based biodiesel production from non-food feedstocks", ***Journal of Environmental Management***, Vol. 249, (2019), 109316. (https://doi.org/10.1016/j.jenvman.2019.109316).
2. Hassan, M.H. and Kalam, M.A., "An overview of biofuel as a renewable energy source: Development and challenges", ***Procedia Engineering***, Vol. 56, (2013), 39-53. (https://doi.org/10.1016/j.proeng.2013.03.087).
3. Yang, W.M., An, H., Chou, S.K., Chua, K.J., Mohan, B., Sivasankaralingam, V., Raman, V., Maghbouli, A. and Li, J., "Impact of emulsion fuel with nano-organic additives on the performance of diesel engine", ***Applied Energy***, Vol. 112, (2013), 1206-1212. (https://doi.org/10.1016/j.apenergy.2013.02.027).
4. Fahd, M.E.A., Wenming, Y., Lee, P.S., Chou, S.K. and Yap, C.R., "Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition", ***Applied Energy***, Vol. 102, (2013), 1042-1049. (https://doi.org/10.1016/j.apenergy.2012.06.041).
5. Alenezi, R.A., Erdiwansyah, Mamat, R., Norkhizan, A.M. and Najafi, G., "The effect of fusel-biodiesel blends on the emissions and performance of a single cylinder diesel engine", ***Fuel***, Vol. 279, (2020), 118438. (https://doi.org/10.1016/j.fuel.2020.118438).
6. Seifi, M.R., Hassan-Beygia, S.R., Ghobadian, B., Desideri, U. and Antonelli, M., "Experimental investigation of a diesel engine power, torque and noise emission using water-diesel emulsions", ***Fuel***, Vol. 166, (2016), 392-399. (https://doi.org/10.1016/j.fuel.2015.10.122).
7. Alahmer, A., "Influence of using emulsified diesel fuel on the performance and pollutants emitted from diesel engine", ***Energy Conversion and Management***, Vol. 73, (2013), 361-369. (https://doi.org/10.1016/j.enconman.2013.05.012).
8. Venu, H. and Appavu, P., "Al_2O_3 nano additives blended Polanga biodiesel as a potential alternative fuel for existing unmodified DI diesel engine", ***Fuel***, Vol. 279, (2020), 118518. (https://doi.org/10.1016/j.fuel.2020.118518).
9. Ninawe, G. and Tariq, M., "Influence of carbon nanotubes as additive in diesel-biodiesel blends in CI engine-an experimental investigation",

International Journal of Sustainable Engineering, (2020), 1-12. (https://doi.org/10.1080/19397038.2020.1790059).

10. Armas, O., Ballesteros, R., Martos, F.J. and Agudelo, J.R., "Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel", ***Fuel***, Vol. 84, No. 7-8, (2005), 1011-1018. (https://doi.org/10.1016/j.fuel.2004.11.015).
11. Baskar, P. and Kumar, A.S., "Experimental investigation on performance characteristics of a diesel engine using diesel-water emulsion with oxygen enriched air", ***Alexandria Engineering Journal***, Vol. 56, No. 1, (2017), 137-146. (https://doi.org/10.1016/j.aej.2016.09.014).
12. Lin, C.Y. and Chen, L.W., "Engine performance and emission characteristics of three-phase diesel emulsions prepared by an ultrasonic emulsification method", ***Fuel***, Vol. 85, No. 5, (2006), 593-600. (https://doi.org/10.1016/j.fuel.2005.09.007).
13. Saravanan, M., Anbarasu, A. and Gnanasekaran, B.M., "Study of performance and emission characteristics of IC engines by using diesel-water emulsion", ***The International Journal of Advanced Manufacturing Technology***, Vol. 69, No. 9-12, (2013), 2531-2544. (https://doi.org/10.1007/s00170-013-5132-5).
14. Lin, C.Y. and Chen, L.W., "Comparison of fuel properties and emission characteristics of two-and three-phase emulsions prepared by ultrasonically vibrating and mechanically homogenizing emulsification methods", ***Fuel***, Vol. 87, No. 10-11, (2008), 2154-2161. (https://doi.org/10.1016/j.fuel.2007.12.017).
15. Ithnin, A.M., Ahmad, M.A., Bakar, M.A.A., Rajoo, S. and Yahya, W.J., "Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade diesel fuel", ***Energy Conversion and Management***, Vol. 90, (2015), 375-382. (https://doi.org/10.1016/j.enconman.2014.11.025).
16. Suresh, V. and Amirthagadeswaran, K., "Combustion and performance characteristics of water-in-diesel emulsion fuel", ***Energy Sources Part A: Recovery Utilization and Environmental Effects***, Vol. 37, No. 18, (2015), 2020-2028. (https://doi.org/10.1080/15567036.2015.1072605).
17. Tsukahara, M., Yoshimoto, Y. and Murayama, T., "Influence of emulsified fuel properties on the reduction of BSFC in a diesel engine", Technical Paper, ***SAE Transactions***, Vol. 98, Section 3: Journal of Engine, (1989), 1795-1804. (https://www.jstor.org/stable/44581063).
18. Park, S., Woo, S., Kim, H. and Lee, K., "Effect of diesel-water emulsified fuel on the NO_x and PM emissions of a diesel engine", ***Energy & Fuels***, Vol. 30, No. 7, (2016), 6070-6079. (https://doi.org/10.1021/acs.energyfuels.6b00089).
19. Lin, C.Y. and Wang, K.H., "Effects of a combustion improver on diesel engine performance and emission characteristics when using three-phase emulsions as an alternative fuel", ***Energy & Fuels***, Vol. 18, No. 2, (2004), 477-484. (https://doi.org/10.1021/ef0300848).
20. Zhang, J., Jiang, D., Huang, Z., Wang, X. and Wei, Q., "Performance and emissions of direct injection diesel engine fueled with diesel fuel containing dissolved methane", ***Energy & Fuels***, Vol. 20, No. 2, (2006), 504-511. (https://doi.org/10.1021/ef0502094).
21. El Shenawy, E.A., Elkelawy, M., Bastawissi, H.A.E., Shams, M.M., Panchal, H., Sadasivuni, K. and Thakar, N., "Investigation and performance analysis of water-diesel emulsion for improvement of performance and emission characteristics of partially premixed charge compression ignition (PPCCI) diesel engines", ***Sustainable Energy Technologies and Assessments***, Vol. 36, (2019), 100546. (https://doi.org/10.1016/j.seta.2019.100546).
22. Yang, W., An, H., Chou, S.K., Vedharaji, S., Vallinagam, R., Balaji, M., Mohammad, F.E.A. and Chua, K.J.E., "Emulsion fuel with novel nano-organic additives for diesel engine application", ***Fuel***, Vol. 104, (2013), 726-731. (https://doi.org/10.1016/j.fuel.2012.04.051).
23. Sudrajad, A., Hirotsugu, F. and Ali, I., "Experimental study of exhaust emissions of W/O emulsion fuel in DI single cylinder diesel engine", ***Modern Applied Science***, Vol. 5, No. 5, (2011), 73-79. (https://doi.org/10.5539/mas.v5n5p73).
24. Kannan, K. and Udayakumar, M., "NO_x and HC emission control using water emulsified diesel in single cylinder diesel engine", ***ARPN Journal of Engineering and Applied Sciences***, Vol. 4, No. 8, (2009), 59-62. (https://www.researchgate.net/publication/239528260).
25. Subramanian, K.A., "A comparison of water-diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions", ***Energy Conversion and Management***, Vol. 52, No. 2, (2011), 849-857. (https://doi.org/10.1016/j.enconman.2010.08.010).
26. Bidita, B.S, Suraya, A.R, Shazed, A., Mohd Salleh, M.A. and Idris, A., "Influence of fuel additive in the formulation and combustion characteristics of water-in-diesel nanoemulsion fuel", ***Energy & Fuels***, Vol. 28, No. 6, (2014), 4149-4161. (https://doi.org/10.1021/ef5002259).
27. Chen, Z.B., Wang, X.C., Pei, Y.Q., Zhang, C., Xiao, M. and He, J., "Experimental investigation of the performance and emissions of diesel engines by a novel emulsified diesel fuel", ***Energy Conversion and Management***, Vol. 95, (2015), 334-341. (https://doi.org/10.1016/j.enconman.2015.02.016).
28. Basha, J.S. and Anand, R.B., "An experimental investigation in a diesel engine using carbon nanotubes blended water-diesel emulsion fuel", ***Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy***, Vol. 225, No. 3, (2011), 279-288. (https://doi.org/10.1177/2041296710394247).
29. Hoseini, S.S. and Sobati M.A., "Performance and emission characteristics of a diesel engine operating on different water in diesel emulsion fuels: Optimization using response surface methodology (RSM)", ***Frontiers in Energy***, Vol. 13, (2019), 636-657. (https://doi.org/10.1007/s11708-019-0646-7).
30. Attia, A.M.A. and Kulchitskiy, A.R., "Influence of the structure of water-in-fuel emulsion on diesel engine performance", ***Fuel***, Vol. 116, (2014), 703-708. (https://doi.org/10.1016/j.fuel.2013.08.057).
31. Ghojel, J., Honnery, D. and Al-Khaleefi, K., "Performance, emissions and heat release characteristics of direct injection diesel engine operating on diesel oil emulsion", ***Applied Thermal Engineering***, Vol. 26, No. 17-18, (2006), 2132-2141. (https://doi.org/10.1016/j.applthermaleng.2006.04.014).
32. Badrana, O., Emeish, S., Abu-Zaid, M., Abu-Rahma, T., Al-Hasan, M. and Al-Ragheb, M., "Impact of emulsified water/diesel mixture on engine performance and environment", ***International Journal of Thermal & Environmental Engineering***, Vol. 3, No. 1, (2011), 1-7. (https://doi.org/10.5383/ijtee.03.01.001).
33. Nadeem, M., Rangkuti, C., Anuar, K., Haq, M.R.U., Tan, I.B. and Shah, S.S., "Diesel engine performance and emission evaluation using emulsified fuels stabilized by conventional and gemini surfactants", ***Fuel***, Vol. 85, No. 14, (2006), 2111-2119. (https://doi.org/10.1016/j.fuel.2006.03.013).
34. Noor El-Din, M.R., El-Hamouly, S.H., Mohamed, H.M., Mishrif, M.R. and Ragab, A.M., "Water-in-diesel fuel nanoemulsions: Preparation, stability and physical properties", ***Egyptian Journal of Petroleum***, Vol. 22, No. 4, (2013), 517-530. (https://doi.org/10.1016/j.ejpe.2013.11.006).
35. Sharma, M. and Kaushal, R., "Performance and emission analysis of a dual fuel variable compression ratio (VCR) CI engine utilizing producer gas derived from walnut shells", ***Energy***, Vol. 192, (2020), 116725. (https://doi.org/10.1016/j.energy.2019.116725).
36. Sayin, C. and Canakci, M., "Effects of injection timing on the engine performance and exhaust emissions of a dual-fuel diesel engine", ***Energy Conversion and Management***, Vol. 50, No. 1, (2009), 203-213. (https://doi.org/10.1016/j.enconman.2008.06.007).
37. Alahmer, A., Yamin, J., Sakhrieh, A. and Hamdan, M.A., "Engine performance using emulsified diesel fuel", ***Energy Conversion and Management***, Vol. 51, No. 8, (2010), 1708-1713. (https://doi.org/10.1016/j.enconman.2009.11.044).
38. Selim, M.Y.E. and Ghannam, M.T., "Combustion study of stabilized water-in-diesel fuel emulsion", ***Energy Sources, Part A: Recovery, Utilization, and Environmental Effects***, Vol. 32, No. 3, (2009), 256-274. (https://doi.org/10.1080/15567030802467621).
39. Koc, A.B. and Abdullah, M., "Performance and NO_x emissions of a diesel engine fueled with biodiesel-diesel-water nanoemulsions", ***Fuel Processing Technology***, Vol. 109, (2013), 70-77. (https://doi.org/10.1016/j.fuproc.2012.09.039).
40. Selim, M.Y.E. and Ghannam, M.T., "Performance and engine roughness of a diesel engine running on stabilized water diesel emulsion", ***Proceedings of 8th International Conference on Engines for Automobiles***, (2007). (https://doi.org/10.4271/2007-24-0132).
41. Abu-Zaid, M., "Performance of single cylinder, direct injection diesel engine using water fuel emulsions", ***Energy Conversion and Management***, Vol. 45, No. 5, (2004), 697-705. (https://doi.org/10.1016/S0196-8904(03)00179-1).
42. Raheman, H. and Kumari, S., "Combustion characteristics and emissions of a compression ignition engine using emulsified jatropha biodiesel blend", ***Biosystems Engineering***, Vol. 123, (2014), 29-39. (https://doi.org/10.1016/j.biosystemseng.2014.05.001).

43. Lin, C.Y. and Lin, H.A., "Engine performance and emission characteristics of a three-phase emulsion of biodiesel produced by peroxidation", ***Fuel Processing Technology***, Vol. 88, No. 1, (2007), 35-41. (https://doi.org/10.1016/j.fuproc.2006.07.008).

44. Seifi, M.R., Desideri, U., Ghorbani, Z., Antonelli, M., Frigo, S., Hassan-Beygi, S.R. and Ghobadian, B., "Statistical evaluation of the effect of water percentage in water-diesel emulsion on the engine performance and exhaust emission parameters", ***Energy***, Vol. 180, (2019), 797-806. (https://doi.org/10.1016/j.energy.2019.04.093).

45. Kinoshita, E., Hamasaki, K., Jaqin, C. and Takasaki, K., "Combustion characteristics for diesel engines with emulsified biodiesel without adding emulsifier", ***Proceedings of 2004 SAE Fuels & Lubricants Meeting & Exhibition***, (2004). (https://doi.org/10.4271/2004-01-1860).

46. Lin, C.Y. and Wang, K.H., "Diesel engine performance and emission characteristics using three-phase emulsions as fuel", ***Fuel***, Vol. 83, No. 4-5, (2004), 537-545. (https://doi.org/10.1016/j.fuel.2003.08.012).

47. Kumar, M.S., Kerihuel, A., Bellettre, J. and Tazerout, M., "Ethanol animal fat emulsions as a diesel engine fuel-Part 2: Engine test analysis", ***Fuel***, Vol. 85, No. 17, (2006), 2646-2652. (https://doi.org/10.1016/j.fuel.2006.05.023).