Evaluating the effect of water percentage in water-diesel emulsion on the engine performance and exhaust emission parameters

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Abstract

This research presents the results of evaluating the effect of water-diesel emulsion usage on the engine performance and its emission parameters under different loading conditions without engine modification. The water was added to neat diesel to form four emulsion blends (2%, 5%, 8% and 10% by vol.) in the presence of 2 volumetric percentage of surfactant. The prepared samples were called E2, E5, E8 and E10, respectively. The mean values of measured engine performance and emission parameters were compared using Duncan's multiple range tests. It was found that emulsions significantly decreased the engine power and torque at 1% probability level ($P<0.01$). The E2 usage improved significantly ($P<0.01$) the engine brake specific fuel consumption (BSFC) and also brake thermal efficiency with 13.1% increase comparing to neat diesel. The significant increase ($P<0.01$) in the engine CO emission and decrease in CO_2 emission was observed when increasing the water content of emulsions. The highest improvement in the engine HC and NO_x emission was obtained for E5. However, the combustion of other emulsion blends increased the HC emission when compared to neat diesel. Generally, the presence of water in diesel increased the oxygen content and decreased the NO_x content of exhaust gas. As a whole, if there is no concern about the negative effect of E5 usage on the engine performance parameters for a certain task, it would be the best suggestion to decrease undesirable noxious emission and also CO_2, which is one of the most important greenhouse gases in the world.

Keywords: Water-diesel emulsion, diesel engine, engine load, engine performance parameters, exhaust emissions.

Introduction

In spite of diesel engine advantages in mass transportation, heavy industries and agricultural sectors, they are one of the major pollution contributors to present time. As vehicle emission standards become stricter, engine manufacturer have to implement different kinds of new methods to meet the requirements of new standards. One of these methods is using water-diesel emulsion, which could be used effectively in all types of diesel engines without the need to engine modification. This emulsion is prepared by homogeneous mixing of water with the neat diesel fuel on volume basis in the presence of an appropriate surfactant to make it stable [1]. Researchers showed significant and sometimes inconsistent effects of water-diesel emulsion usage in the performance and emission of diesel engines. Fahd et al. [1] and Yang et al. [2] reporetd power output reduction using water-diesel emulsion as compared to neat diesel fuel. However, research work in Refs. [3 and 4] showed higher power output for water-diesel emulsion containing a small amount of water. Although Tsukahara et al. [5] reported the reduction in brake specific fuel consumption (BSFC) by expressing several reasons, Alahmer et al. [6] and Cui et al. [7] found the brake specific fuel consumption increment by using of water-diesel emulsion comparing to neat diesel fuel. NO_x reduction due to lower peak temperature of the flame was reported in the majority of studies about the water-diesel emulsion [8]. The reason of temperature reduction is the latent heat from the evaporation of water in the emulsion that absorbs the heat during combustion [9].The effect of water-diesel emulsion combustion on unburnt hydrocarbon (UHC) and CO emission is not the same. While Cui et al. [7] and Subramanian [10] reported UHC and CO emissions increment for emulsion comparing to neat diesel, Kumar et al. [11] and Attia and Kulchitskiy [12] showed slight reduction in these emissions. It also is noteworthy that Yang et al. [2] found no obvious difference between engine UHC and CO emissions using emulsion and neat diesel. There are very few studies that measured O_2 and CO_2 emissions for emulsion combustion. According to Alahmer [4] lower CO_2 emission, which is the main product of exhaust emission, was obtained for emulsion as compared to neat diesel. However, another study revealed that the difference between CO_2 emissions of emulsion and neat diesel combustion depended to engine loading condition and the former is greater at high engine load [13]. The study of Alahmer [4] also showed higher oxygen content of exhaust emission when using emulsion comparing to neat diesel.

Literature survey revealed that there is inconsistent and in some cases limited information concerning the effect of water-diesel emulsion on the performance and exhaust emission of diesel engine at different engine loads. Also statistical analysis was rarely implemented to analyze the diesel engine performance and exhaust emission using water-diesel emulsion to evaluate the level of water presence effect in neat diesel on the engine performance and exhaust emission parameters. So, the aim of this study is a comprehensive statistical analysis of the diesel engine power, torque, BSFC, brake thermal efficiency and exhaust emissions using water-diesel emulsion with different water percentages.

Materials and Methods

2%, 5%, 8% and 10% by Vol. of water were added to neat diesel to form E2, E5, E8 and E10 emulsions. A 3000 rpm rod stirrer (AT-MD 10, FALC Instruments) was used to prepare emulsions. 2 volumetric percentage of Span 80 (Sorbitan monooleate) was added to sample during mixing to reduce the surface tension of the water through adsorbing at the liquid–gas interface. The surfactant also decreased the interfacial tension between the neat fuel and water due to the adsorbing effect at the liquid–liquid interfaces [6]. A 1.248 L four stroke, two cylinder, air-cooled, direct injection diesel engine was used in the study (Table 1). An eddy current Borghi e Saveri dynamometer with ±0.1 kW, ±0.1 Nm and ±1 rpm accuracies measured the engine power, torque and speed, respectively. The maximum engine speed (2750 rpm) was selected as the engine operating speed in this study. To obtain the maximum operating power of the engine, it is loaded by the dynamometer at operating speed until the engine torque and its rotational speed started to decrease. Then, measurements were performored at 25%, 50%, 75% and 100% of maximum torque. An AVL733S fuel meter with 10 Hz measuring frequency and 0.12% measuring accuracy was used to measure fuel consumption (FC) in gr/hr. To obtain the BSFC of the engine, which is a measure of fuel efficiency, the following equation is used:

$$BSFC = \frac{FC}{P} \quad (1)$$

Where P is the power output of the engine (kW). The measurements of engine emissions (NO_x, CO, CO_2, UHC and O_2 contents in the exhaust gas) was carried out by an AVL DiTEST MDS 650, which its specifications were given in Table 2. Fig. 1 shows the shematic diagram of the engine testing setup. The effects of engine load and the fuel blend type (independent variables) on the engine performance and exhaust emission parameters (dependent variables) were statistically analyzed using the two factors completely randomized design procedure. The Duncan's multiple range tests was also implemented to evaluate the significant difference between the mean values of vaiables. In case of not existing significant difference at 1% probability level between the mean of measured dependent values, common letters were used. The mean values of dependent variables were obtained by averaging three measured values.

Table 1. 9LD 625-2 Lombardini diesel engine specifications

Combustion system	Direct injection
Number of cylinder	2
Compression ratio	17.5
Bore × stroke	98.6 × 127 mm^2
Engine displacement	1.248 L
Maximum power at 2800 rpm	18.2 kW
Maximum torque at 2000 rpm	67 N m

Table 2. Emission meter specification

Measurement	Unit	Range	Accuracy
NO_x	ppm vol.	0-5000	1
CO	Vol %.	0-15	0.01
CO_2	Vol %.	0-20	0.1
UHC	ppm vol.	0-30000	1 for values ≤ 2000 10 for values > 2000
O_2	Vol %.	0-25	0.01

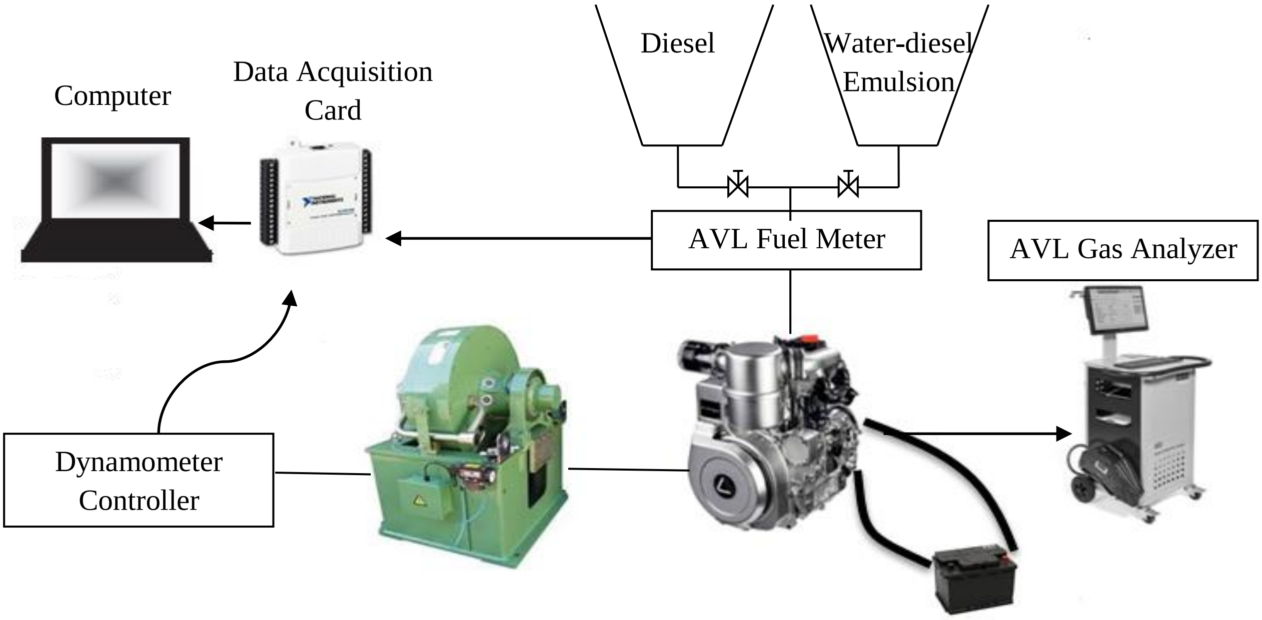


Fig. 1. Schematic of experimental setup.

Resluts and Discussion

The results of Duncan's multiple range tests to compare the mean values of the engine power versus the fuel blends and engine load (Fig. 2) shows that the engine power output decreased with the increase in water percentage in fuel. This could be attributed to the decrease in the calorific value of emulsions when compared to neat diesel fuel. The results of this figure for E2 is opposite to the explanation provided by Seifi et al. [3] who reported higher power output for E2 compared with neat diesel. The reason of such contrariety could be explained by Ithnin et al. [14], which related the inconsistency of the experimental results to the size of dispersed water and also diesel engine type. From Fig. 2 it can be seen that, as expected, the increase in the engine load increases the power output.

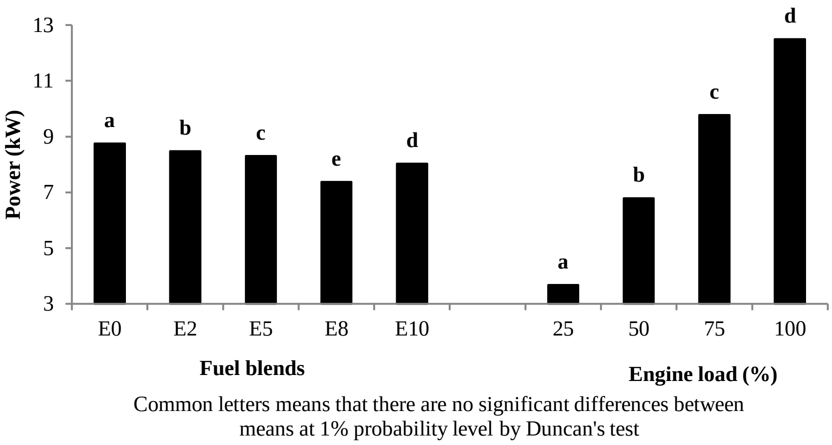
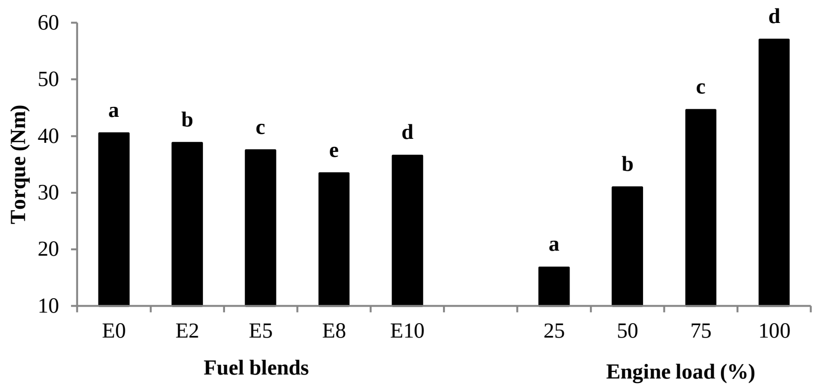


Fig. 2. The engine power output for different fuel blends under varying load.

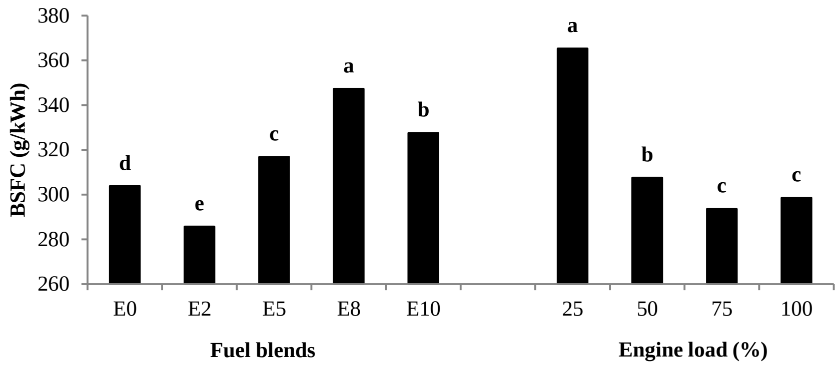
Comparing the mean values of the engine torque and its load versus the fuel blends using Duncan's multiple range tests (Fig. 3) shows similar results to engine power. E8 with 17.5% decrease in the engine torque comparing to neat diesel showed the minimum torque output followed by E10 with 9.71% decrease.



Common letters means that there are no significant differences between means at 1% probability level by Duncan's test

Fig. 3. The engine torque output for different fuel blends under varying load

Fig. 4 presents the results of Duncan's multiple range tests to compare mean values of BSFC versus the fuel blends and engine load. From this figure, it can be seen that adding 2% by vol. water to neat diesel fuel significantly lowered the BSFC of the engine at 1% probability level. Although the calorific value of this emulsion is lower than the neat diesel fuel, the lower BSFC for the emulsion could have resulted from better atomization of this emulsion due to the micro explosion process in addition to having comparable calorific value to neat diesel. Further addition of water to neat diesel increased BSFC as a result of fuel calorific value and power output decrement. Alahmer et al. [6] reported lower BSFC for water-diesel emulsions containing small amount of water. The results of Fig. 4 also showed BSFC decrement when increasing engine load, which could be the result of the combustion and fuel-air mixing process improvement (greater evaporation and better atomization process) due to higher in-cylinder temperature after successive working of engine. Ithnin et al. [13] reported similar results for a low-grade diesel fuel.



Common letters means that there are no significant differences between means at 1% probability level by Duncan's test

Fig. 4. The engine BSFC for different fuel blends under varying load

Fig 5 shows the engine brake thermal efficiency (η_{bth}) values, which is defined as brake power output of an engine (P_b) as a function of heat released from the consumed fuel [15]. It could be calculated by [16]:

$$\eta_{bth} = \frac{P_b}{\dot{m}_f \times Q_{HV}} = \frac{3600}{BSFC \times Q_{HV}} \quad (2)$$

where $\dot{m}_f$ is the consumed fuel mass flow rate and Q_{HV} is the heating value per unit-mass of the fuel (MJ/kg). Fuel calorific value measurements showed the decrease in fuel heating value with the presence and increase in water percentage of emulsion, where 47.21, 44.36, 43, 42.78 and 41.73 MJ/kg were obtained for neat diesel, E2, E5, E8 and E10, respectively. The trend of brake thermal efficiency curve going in the opposite direction of BSFC, which is similar to the results of Lin and Chen [16]. From Fig. 5, it can be seen that the highest thermal efficiency was observed for emulsion with the lowest amount of water, which could be attributed to BSFC decrement for this fuel blend comparing to neat diesel. The results of this figure also showed higher thermal efficiency for E5 and E10 compared to neat diesel, which implied the better and more complete combustion for emulsion blends and could be a remarkable advantage for water-diesel emulsion.

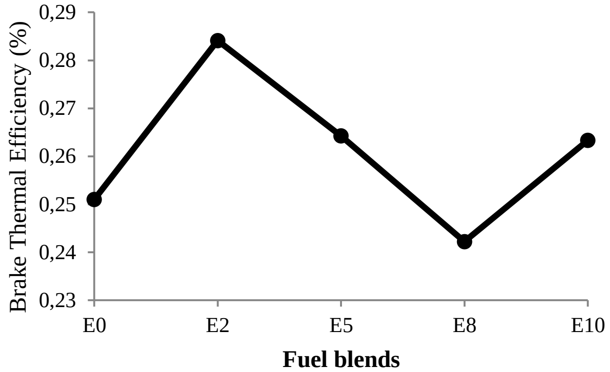


Fig. 5. Brake engine thermal efficiency values for different fuel blends.

The comparison of mean values of engine CO emission versus fuel blends and engine load using Duncan's multiple range tests was shown in Fig. 6. The results showed significant increase in engine CO emission at 1% probability level for E5 and E10. The increse could be attributed to the water presence in the fuel, which slows down the oxidation process of CO to CO_2 by decreasing the combustion temperature [7]. Another reason could be the high amount of OH radicals due to the presence of water, which increases oxidation of carbon to CO [17]. It can also be found from Fig. 6 that as the engine load increased from 25% to 50%, the engine CO decreases. However, further increase in engine load resulted in the increase in CO emission. Similar trend in CO emission versus engine load was reported by Ithnin et al. [13]. Slow oxidation process of CO to CO_2 due to low combustion temperature could be the reason of high CO content of exhaust gas at 25% load. According to De Vita [18], oxygen shortage inside the jet core of the fuel impinged on the walls at the end portion of the injected fuel could yield greatest engine CO emission at full load condition.

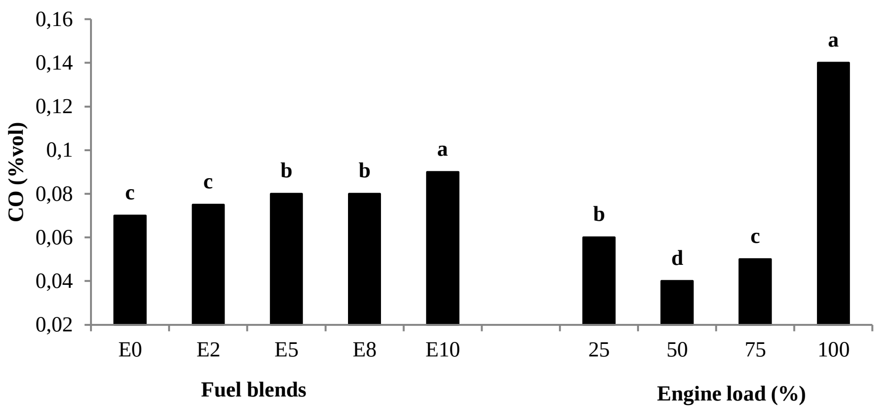


Fig. 6. The engine CO emission for different fuel blends under varying load

Fig 7. depicts the results of Duncan's multiple range tests to compare the mean values of engine CO_2 emission versus the fuel blends and engine load. It can be seen that the presence of 5 volumetric percentage of water and higher significantly decreased the engine CO_2 emission at 1% probability level as compared to neat diesel fuel and E2. This could be attributed to the decrement of combustion temperature that slows down the oxidation process of CO to CO_2.The increase in CO_2 emission with the increase in water content from 8% to 10% could be attributed to greater oxygen content of E10, which enhanced the oxidation process of CO to CO_2. Alahmer [4] reported greater CO_2 emission for some emulsion blends with higher water contents. Fig. 7 also shows that the engine load increment significantly increased the engine CO_2 emission at 1% probability level. The increase could be due to temperature increment when increasing the engine load, which enhanced the oxidation process of CO to CO_2. Kecojevic and Komljenovic [19] and Ogunkoya et al., [20] reported the increase in diesel engine CO_2 emission with an increase in the engine load.

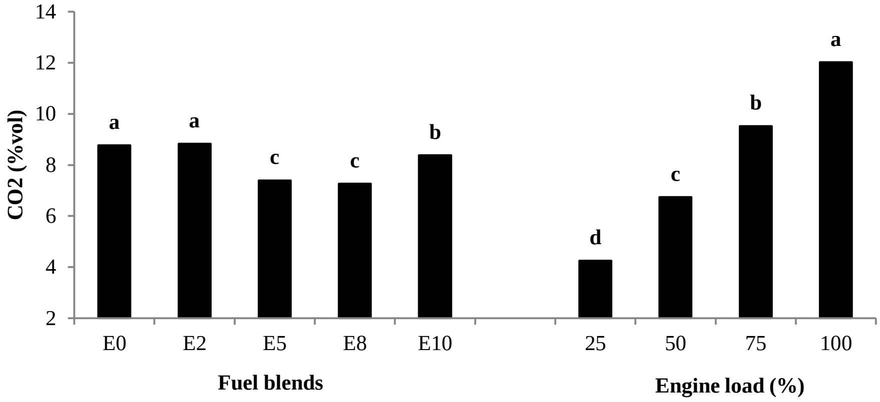


Fig. 7. The engine CO_2 emission for different fuel blends under varying load

The results of comparing mean values of engine HC emission using Duncan's multiple range tests (Fig. 8) showed the smallest value for E5. The reason of such phenomenon could be the micro explosion process, which was happened from rapid evaporation of water droplet and resulted in higher combustion efficiency and lower engine HC emission. Like to what was found for CO emission, the highest HC emission was observed for E10. The lowest combustion temperature for this emulsion with the greatest percentage of water could cause the increase in HC emission. Fig. 8 also showed significantly ($P<0.01$) greater HC emission at minimum and maximum engine loads. The low combustion temperature at 25% load could result in incomplete combustion and HC emission increment. At full load, the air-fuel ratio reduces to its minimum value [21], therefore, there is a lack of oxygen in the cylinder with a significant increase at 1% probability level ($P<0.01$) in HC emission. Kumar et al. [11] reported similar results for a diesel engine.

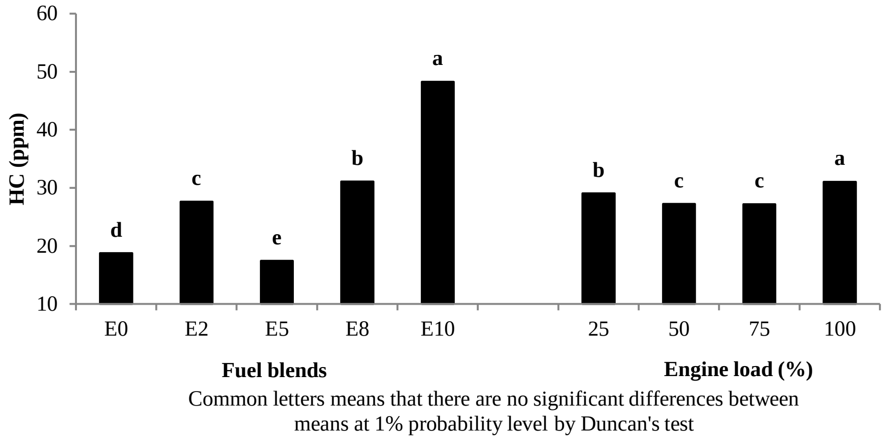


Fig. 8. The engine HC emission for different fuel blends under varying load

The mean values of oxygen emitted for different fuel blends and engine loads were compared using Duncan's multiple range tests and results were depicted in Fig. 9. It could be noted that the combustion of E5 and E8 emulsions yielded greatest oxygen emission. The reason of such increment could be explained by the engine CO_2 emission results (Fig. 7), which reported the lowest carbon dioxide content for emulsions with 5 and 8 volumetric percentage of water. Therefore, the combustion of these two emulsions may result in the lowest amount of CO oxidation to CO_2 and more oxygen remained in the engine cylinder. Fig. 9 also shows the significant engine O_2 emission reduction at 1%probability level with engine load increment. The reason of such phenomenon could be air-fuel ratio reduction with load increment, which was explained in previous section.

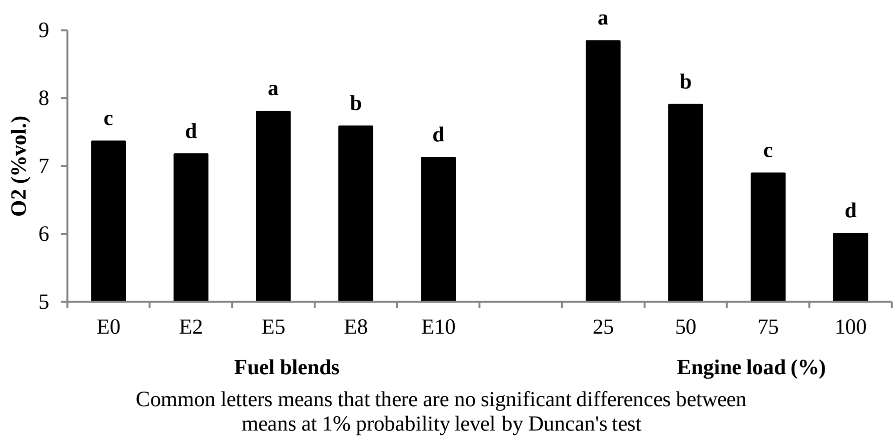


Fig. 9. The engine O_2 emission for different fuel blends under varying load

Fig. 10 presents the results of Duncan's multiple range tests to compare the mean values of the engine NO_x emission versus the fuel blends and engine load. The combustion of all emulsion blends showed significantly lower NO_x emission ($P<0.01$) than neat diesel, which could be attributed to the combustion temperature reduction due to the presence of water in emulsions [9]. The usage of E5 yielded the minimum engine NO_x with 31% decrease compared to neat diesel. Similar to HC emission (Fig. 8) the micro explosion process along with combustion temperature reduction due to the presence of water decreased the NO_x emission. Attia and Kulchitskiy [12] reported lower NO_x emission for water-diesel emulsion. Ballester et al. [22] found NO_x decrease in cylinder regions where the combustion process is near to completion. The increase in the engine load increased the combustion temperature and caused significant increase in engine NO_x emission at 1%probability level (P<0.01). Ithnin et al. [13] reported similar results with load increment.

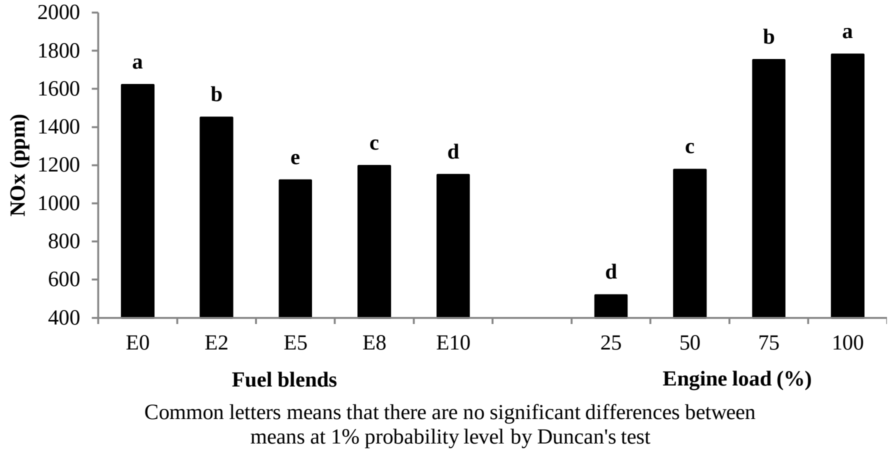


Fig. 10. The engine NO_x emission for different fuel blends under varying load

Conclusion

The following conclusions were obtained from this experimental study:

1. The addition of water to neat diesel decreased significantly (P<0.01) the engine power and torque.
2. When both water and diesel were considered as consumed fuel, significant decrease (P<0.01) in engine BSFC was observed for E2 comparing to neat diesel. However, the combustion of other emulsions increased the engine BSFC significantly (P<0.01).
3. Improving the engine brake thermal efficiency with the presence of water in diesel could be considered as a great advantage for emulsion combustion in diesel engine.
4. As water percentage increased in diesel fuel, the engine CO emission increased significantly (P<0.01). The engine running at 50% load is considered to be the best in reducing engine CO emission.
5. The presence of 5 volumetric percentage of water and greater, decreased significantly (P<0.01) the engine CO_2 emission. Significant increase was found with engine load increment.
6. E5 is the only emulsion with significantly (P<0.01) lower HC emission than neat diesel.
7. Emulsion combustion yielded greater oxygen content than neat diesel in the exhaust gas. Lower oxygen content was observed with load increment.
8. The formation of NO_x is found to be significantly (P<0.01) lower for emulsions when compared to neat diesel. The more the engine operated closer to full load, the slower the engine load increased.

As a whole, although according to literature the water in diesel emulsion could be considered as a greener fuel for diesel engine when compared to neat diesel, it was found that fuel effects on the engine performance and exhaust emission parameters were totally dependent to water content of emulsion. Analyzing the exhaust emission using Duncan's multiple range tests showed the optimum result for emulsion containing 5 volumetric percentage of water. Considering the 5% and 7% decrease in the engine power and torque and 4.3% and 5.2% increase in the engine BSFC and brake thermal efficiency for the diesel engine fuelled with E5, when there is no concern about engine overload, this emulsion could be considered as the best alternative for diesel engine.

References

[1] Fahd EA, Wenming Y, Lee P, Chou S, Yap C. Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition. Appl Energy 2013;102:1042–9.

[2] Yang WM, An H, Chou SK, Chua KJ, Mohan B, Sivasankaralingam V, et al. Impact of emulsion fuel with nano-organic additives on the performance of diesel engine. Appl Energy 2013;112:1206–12.

[3] Seifi MR, Hassan-Beygi SR, Ghobadian B, Desideri U, Antonelli M. Experimental investigation of a diesel engine power, torque and noise emission using water– diesel emulsions. Fuel 2016;166:392–309.

[4] Alahmer A. Influence of using emulsified diesel fuel on the performance and pollutants emitted from diesel engine. Energy Convers Manage 2013;73:361–9.

[5] Tsukahara M, Yoshimoto Y. Influence of emulsified fuel properties on the reduction of BSFC in a diesel engine. SAE paper 891841; 1989.

[6] Alahmer A, Yamin J, Sakhrieh A, Hamdan MA. Engine performance using emulsified diesel fuel. Energy Convers Manage 2010;51:1708–13.

[7] Cui X, Helmantel A, Golovichev V, Denbratt I. Combustion and emissions in a light-duty diesel engine using diesel-water emulsion and diesel-ethanol blends. SAE paper 2009-01-2695; 2009.

[8] Basha JS, Anand RB. An experimental study in a CI engine using nanoadditive blended water–diesel emulsion fuel. Int. J. Green Energy 2011;8:332–48.

[9] Maiboom A, Tauzia X. NOx and PM emissions reduction on an automotive HSDI Diesel engine with water-in-diesel emulsion and EGR: an experimental study. Fuel 2011;90:3179–92.

[10] Subramanian KA. 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 Convers. Manag. 2011;52:849–857.

[11] Kumar MS, Bellettre J, Tazerout M. Investigations on a CI engine using animal fat and its emulsions with water and methanol as fuel, SAE paper 2005-01-1729; 2005.

[12] Attia AMA, Kulchitskiy A.R. Influence of the structure of water-in-fuel emulsion on diesel engine performance. Fuel 2014;116:703–8.

[13] Ithnin AM, Ahmad MA, Abu Bakar MA, Rajoo S, Yahya WJ. Combustion performance and emission analysis of diesel engine fuelled with water-indiesel emulsion fuel made from low-grade diesel fuel. Energy Convers Manage 2015;90:375–82.

[14] Ithnin AM, Noge H, Abdul Kadir H, Jazair W. An overview of utilizing water-in diesel emulsion fuel in diesel engine and its potential research study. J Energy Inst 2014;87:273–88.

[15] Ferguson CR, Kirkpatrick AT. Internal combustion engines. Singapore, Wiley, 2nd ed.; 2001.

[16] Lin CY, Chen LW. Engine performance and emission characteristics of three-phase diesel emulsions prepared by an ultrasonic emulsification method. Fuel 2006;85(5):593-600.

[17] Koc AB, Abdullah M. Performance and NOx emissions of a diesel engine fueled with biodiesel-diesel–water nanoemulsions. Fuel Process Technol. 2012;109:70–7.

[18] De Vita A. Multi-cylinder DI diesel engine tests with unstabihzed emulsion of water and ethanol in diesel fuel. SAE paper 890450; 1989.

[19] Kecojevic V, Komljenovic D. Impact of bulldozer's engine load factor on fuel consumption, CO2 emission and cost. AM J ENVIRON SCI 2011;7(2):125-31.
[20] Ogunkoya D, Li S, Rojas OJ, Fang T. Performance, combustion, and emissions in a diesel engine operated with fuel-in-water emulsions based on lignin. Appl Energy 2015;154:851-61.
[21] Rajput RK. Internal combustion engines. Laxmi Publications, India; 2005.
[22] Ballester JM, Fueyo N, Dopazo C. Combustion characteristics of heavy oil-water emulsions. Fuel 1996;75:695–705.