Optimization of Water Emulsion in Diesel on the Engine Performance and Emission by Using a CRDI Turbocharged Diesel Engine at Different Load

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Abstract
Water-diesel emulsion fuel is potential alternative fuels for a diesel engine is to reduce dependence on fossil fuels and emissions of Nitrogen Oxides (NOx). A study on the effect of using emulsified diesel fuel on the engine performance and emissions of four cylinder turbocharger common rail with direct injection diesel engine was conducted to investigate the engine combustion efficiency and the emissions produced during the process. Two types of emulsified diesel was produced subsequently the fuel was prepared in the proportion of W5D (5%-water, 93%-diesel, 2%-surfactants) and W10D (10%-water, 88%-diesel, 2%-surfactants) by volume with a hydrophilic-lipophilic balance of 10. An experimental investigation was conducted with respect to type of fuel injected, engine speed and engine load. The data from experimental was used to simulate the design of experiment (DOE) by using response surface method (RSM). Engine power, brake specific fuel consumption, brake thermal efficiency, nitrogen oxide, carbon monoxide and carbon dioxide have been investigated. A 6% of water in diesel was found to be optimal values for emulsified diesel operation in the test engine of 50% load at 2733 rpm. The results of this study revealed that at optimal input parameters, the values of the BTE, BSFC, NOx, CO and CO_2 were found to be 24.91 kW, 243 g/kWh, 517.08 ppm, 0.714 ppm and 51.3 ppm, respectively.

Keywords: Emulsified diesel, DI diesel engine, engine performance and emission

Introduction

The cutting-edge technologies through combination of common-rail , direct injection, turbocharging, and cooled EGR are being rigorously studied in order to substantially enhance the fuel economy of compression ignition (CI) diesel engines. In the past decades, diesel engine has become the premier transportation system for middle and heavy use. Diesel engines are compact, lightweight, and easy to operate. Diesel engines do not need high maintenance, very flexible, high thermal efficiency and suitable for a variety of transportation and industrial uses. These given characteristics, the diesel engine can be used to meet future demand by using fuel with high thermal heat, as well as having a low emission rate.

Modification on fuel properties by adding water in diesel fuel is seen as the way to control performance and emissions of the engine as many researchers reported in literatures. There are several researcher reported that water in diesel can reduce NO_x, CO and smoke simultaneously. The NO_x emission decreased radically due to thermal, dilution and chemical effects (improvement of OH radicals) of water (Attia & Kulchitskiy, 2014; Chang et al., 2013; Debnath et al., 2015; Yahaya Khan et al., 2014). The emissions are regarding to the percentage ratio water emulsion over the diesel fuel as reported in the literature. Most of the studies stated that 15% water-diesel emulsion relied best to control the NO_x emission of the engine (Nadeem et al., 2006).

This study goals to investigate the contribution of water usage in CI diesel engines area through the performance and emissions characteristics with the influences of fuel-water blend and engine loads by using Response Surface Method (RSM). It is believed that the combined effects of factors from engine loads and fuel-water blends on engine performance and emissions characteristics have yet been explored in great detail. Therefore, the novelty of this study lies on the combined effects of factors from engine loads and fuel-water blends for six engine performance and emissions responses; brake power, BSFC, BTE, NOx, CO and CO_2. This research also aims to optimize the combination of the above-mentioned factors to attain immediate improvement in engine performance and reduction of exhaust emissions in a CI diesel engine fueled by water blends. The optimize fuel blends results are then compared with the diesel baseline fuels. The ratio of water used are 5% (W5D) and 10% (W10D), of volumes in diesel fuel operated at various loads varied from 20% to 50% at constant speed of 2000 rpm. It worthy to mentioned RSM is accomplished of predicting data that is not measured in experimental analysis.

Response Surface Methodology

RSM is a combination of a numerical and a statistical technique. It was used for developing, improving, and optimizing the data. Numerical models are valuable tools for simulation and optimization of engine performance and emission analysis. Beside them, the statistical models would help in improving operating parameters and performance of the experimental results. The statistical modeling has brought the advantage to researchers to get efficient and economical designs of results data. The three steps were used in the experimental design for this study; design and experiments, response surface modeling by using regression and optimization. In this study, response surface experimental design was applied for the investigation of water addition in diesel fuel. The central composite design (CCD) procedure was used as response surface method (RSM). In this investigation, CCD which is well suited for fitting of the complicated surfaces was picked out for the experimental design. CCD usually works well for the process optimization and is an effective design that is perfect for the chronological experimentation. This method also allows a reasonable amount of information for lack of fit testing, while not involving an unusually large number of test points. CCD can be applied as an effective method to develop the second-order response models. The CCD consists of three sections including the full or fractional factorial design points (minimum -1 to maximum +1 value), axial points and the center point. The RSM design of experiment was carried out using Design Expert version 7.0.0 software to investigate engine performance and emission.

Material and Methods

The experimental setup consists of a four cylinder diesel engine, an engine test bed and a data acquisition system in control room. The schematic of the experimental setup is shown in Figure 1. The engine was coupled with the engine dynamometer by a coupling shaft. A 150 kW Dynalec Controls eddy current dynamometer was used to measure the brake torque and calculated brake power. The fuel flow rate was recorded using the AIC branded fuel flow meter with a precision of 1%. The fuel line was adapted with a fuel return valve to flow the excess fuel back into the engine. a Benetech GM8903 hot wire anemometer used to measured air flow rate with laminar speed of 0.001 m/s. KANE Autoplus 5-2 gas analyser was used to recorded emissions data and relative air–fuel ratio. The engine speed and engine throttle position were controlled by the engine dynamometer controller inside the engine room. The engine cooling water system from the external tank was used to manage and keep a temperature of 80°C engine temperature.

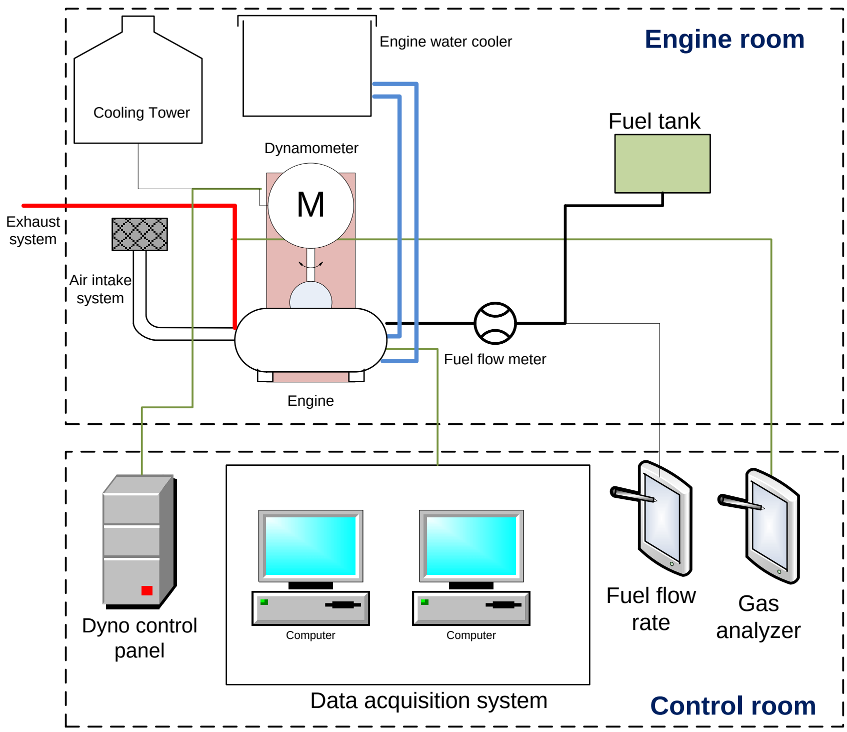

Figure 1: Schematic diagram of the experimental setup

The Isuzu 4JJ1 engine as shows on Table 1 was used in this experiment. The engine was tested at different loads and engine speeds (1000 rpm to 3000 rpm) using different percentage of Diesel with water (5% and 10%) blends. Researchers summarized the W5D (Water emulsion in diesel 5 %) and W10D (Water emulsion in diesel 10 %). At the beginning of each test, the throttle position was adjusted to give a speed of 1000 rpm at a lowest dynamometer load. In the experiments, the load was increased slowly as the engine speed increase by 500 rpm up to 3000 rpm. For each engine speed, the torque was incrementally by 30%, 35% and 50% applied while the fuel consumption rate was recorded. The engine was started with the base diesel fuel first and left to warm up for about 25 to 30 min, and then the Water emulsion in diesel blend was gradually introduced. At the end of each test, the engine was run using base diesel fuel for about 30 to 45 min in order to flush the fueling system from any blended fuel residues.

Table 1: Specification of tested engine

Engine Parameters	Value
Model	Isuzu 4JJ1 (Turbocharged)
Bore (mm)	95.4
Stroke (mm)	104.9
Displacement (L)	2.999 L
Number of cylinders	4 in-line
Compression ratio	17.5

Table 2 shows properties of blends fuel while

Table 3 representation of the details of water emulsion in diesel fuels preparation of water emulsion in diesel (WD). Initially, the importance of the surfactant was investigated for the preparation of the WD emulsion fuel. A mechanical agitator set at an agitation speed of 1000 rpm was used to mix the water and diesel without surfactants for 30 min.

Table 2: Properties of blends fuel

Fuel Properties	Unit	Diesel fuel	W5D	W10D
Density at 20°C	kg/m^3	820	829	838
Cetane number	-	50	47.5	45
Kinematic Viscosity at 40°C	mm^2/s	2.6	2.5	2.4
Lower Heating Value	MJ/kg	43.3	41.1	38.9
Specific heat capacity	J/kg°C	1850	1966	2082
Flash point	°C	52	49	47
Oxygen	%weight	0	4.4	8.9

Table 3: Details of water emulsion in diesel fuels

No	Diesel-water fuel	Diesel (%) by vol.	Water (%) by vol.	Surfactants	
				Span 80 (%) by vol.	Tween 80 (%) by vol.
1	Diesel	100	0	0	0
2	W5D	93	5	1	1
3	W10D	88	10	1	1

Subsequently, the prepared fuel was kept in the test tubes for the stability investigation under static conditions. It was observed that within fifteen minutes there was a major separation of water and diesel in the test tube. Henceforth, it was inferred that a surfactant was needed to prepare the stable water-emulsion fuel. The details of surfactants with a mixture of Span80 and Tween80 and their proportions are tabulated in the Tables 4. Fuel beaker and laboratory overhead paddle stirrers are utilized to prepare the stable WD emulsion fuel in two phases. In the first phase, the surfactants Span80 (HLB = 4.3) and Tween80 (HLB = 15) are filled in the reactor vessel with 2% volume and subjected for agitation at a constant speed of 1000 rpm. Refer to Roila et.al, 2% of surfactant and agitation speeds more than 900 rpm are the best mixing for emulsion fuel (Roila et al., 2008). After the agitation, both the surfactants mixed thoroughly and kept in a separate container.

Results and Discussion

Analysis of engine brake power

The response surface profile for a quadratic model of brake power is shown in Figure 2(a) contour plot and Figure 2(b) three dimensional (3D) plots at 2000 rpm. Brake power well-defined as a one of engine performance characteristics conjointly bring up to usable power delivered by the product of multiplication of engine torque and angular speed produced by an engine (Senthil Kumar & Jaikumar, 2014). The relation between brake power, engine load (A), water percentage (B) and speed (C) mention in Eq. (1)

$$Power = 3.94 - 0.44A + 8.81 \times 10^{-3}B + 5.03 \times 10^{-3}C + 1.92 \times 10^{-3}AB - 2.78 \times 10^{-5}AC + 3.7 \times 10^{-3}BC + 0.04A^2 - 5.16 \times 10^{-3}B^2 - 3.97 \times 10^{-6}C^2 \quad (1)$$

According to the contour plot in Figure 2 (a), base diesel achieved a higher engine brake power at any engine load in comparison to any percentage water emulsion in diesel. However at high percetage of water contain in diesel (W10D), engine brake power are close to base diesel. This indicates that, although addition of water emulsion in diesel fuels reduced the low heating value, it is believed that the dominance effects of oxygen content provided improvement in thermal efficiency, and thus greater engine output in brake power was obtained.

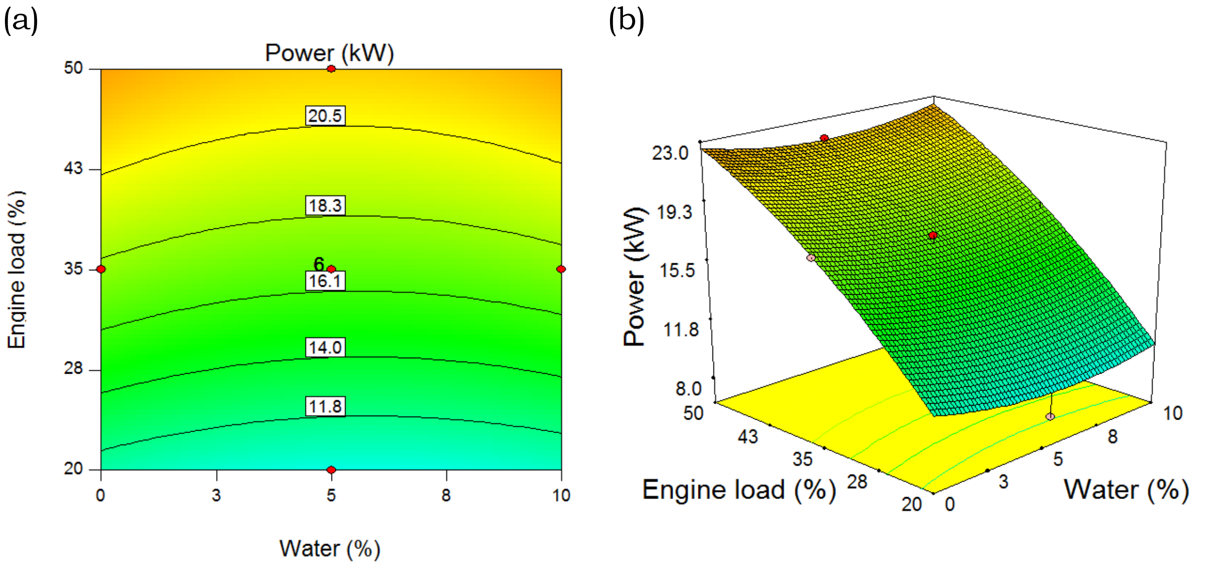

Figure 2: Interactive plot for engine brake power at different engine load and fuel blends at speed of 2000 rpm

Brake Thermal Efficiency Analysis

Figure 3 (a) and (b) show the contour and 3D plot for various load of a quadratic model of BTE at 2000 rpm engine speed and various fuel blends. Thermal efficiency is a function of the engine brake power to the heat input of BSFC and the low heating value. Compared to the BSFC graph trend in Figure 4, BTE is roughly inversely proportional to the BSFC. As can be seen in Figure 3(b) the BTE increased with an increase in engine load, but slightly decrease with increasing of water content. From the contour graph we can see the trend of optimization of BTE in the region of 40% to 50% load and 0% to 5% of water content. This circumstance can be explained considering that a faster burning rate resulted from higher micro-explosion of the fuel blends contributed by the water, leading to a shorter combustion duration and hence less useful effective power losses, thus increasing the BTE . Eq. (2) showed relation between BTE with water percentage (A), engine load (B) and speed (C).

$$BTE = 18.12 + 2.23A + 0.12B - 1.74 \times 10^{-3}C - 0.02AB - 2.7 \times 10^{-4}AC + 3.26 \times 10^{-4}BC - 0.16A^2 - 6.06 \times 10^{-3}B^2 - 1.95 \times 10^{-6}C^2 \quad (2)$$

Brake Specific Fuel Consumption Analysis

Figure 4 (a) and (b) depicts the contour and three-dimensional (3D) plot at 2000 rpm for a quadratic model of BSFC for different engine speeds and fuel blends. Obviously, a robust correlation fuel used with respect to engine brake power. Eq. (3) showed relation between BSFC with water % (A), engine load (B) and speed (C).between BSFC and both water content and engine load. Precise fuel intake is the total of

$$BSFC = 291.79 - 28.52A - 2.34B + 0.16C - 0.12AB + 8.08 \times 10^{-3}AC - 8.63 \times 10^{-3}BC + 3.75A^2 + 0.21B^2 + 3.18 \times 10^{-5}C^2 \quad (3)$$

Figure 4 (b) shows that BSFC is perceived to decline with the rise in engine speed for all experimented fuels, and a further increment in engine loads results in increasing BSFC.

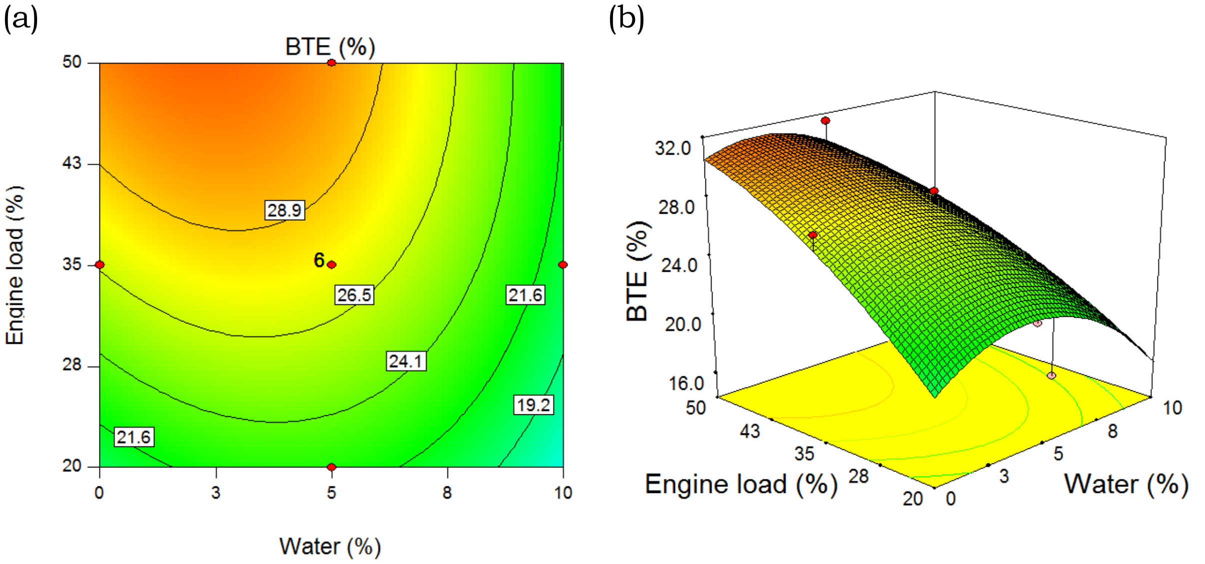

Figure 3: Interactive plot for engine BTE at different engine load and fuel blends

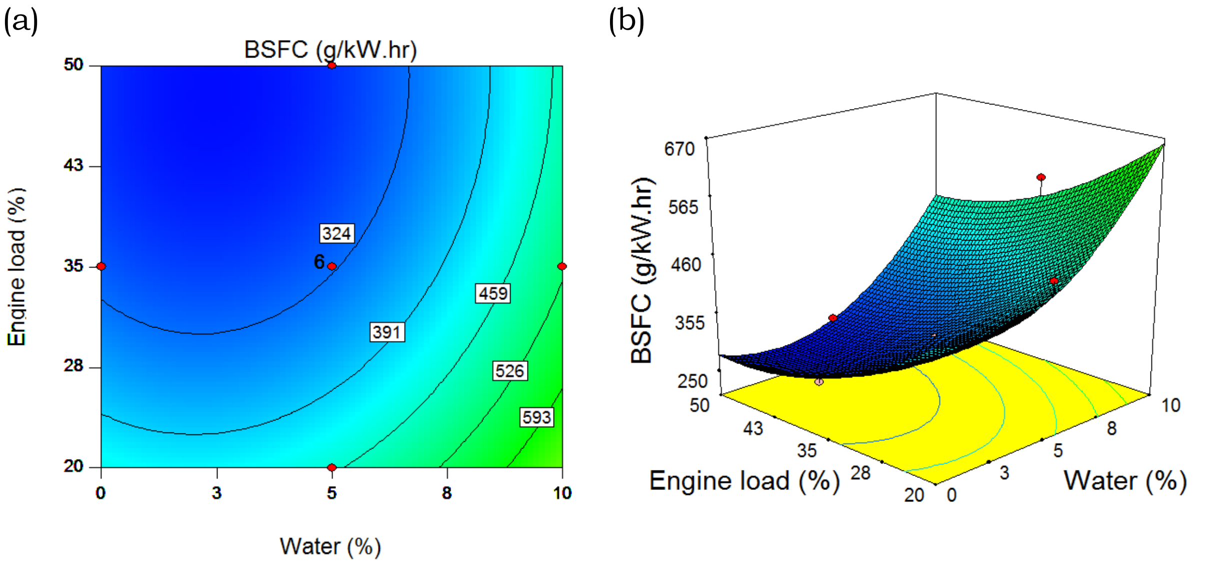

Figure 4 : Interactive plot for engine BSFC at different engine load and fuel blends

Nitrogen Oxide Analysis

Figure 5 (a) and (b) shows the contour and three-dimensional (3D) plot at 2000 rpm engine speed for a quadratic model of engine exhaust emissions of NOx for W5D and W10D fuel-water blends tested at various engine loads. The engine dissipate discharges of NOx made due to the combustion temperature, residence time, effect of combustion area, and oxygen concentration as defined in the Zeldovich mechanism (Masum et al., 2013). The Nitrogen Oxide, NOx are a group of gases from the combination of dinitrogen tetroxide (N_2O_4), nitrogen dioxide (NO_2), nitrous oxide (N2O), nitric oxide (NO), dinitrogen trioxide (N_2O_3) and dinitrogen pentoxide (N_2O_5). But the primary group in NOx are NO and NO2. There was a noteworthy monotonically increasing trend in NOx exhaust emissions corresponding to the engine loads. However, as the fuel blends increased from W5D to W10D, the NOx emissions tended to decrease, as shown in Figure 5(b). From the contour plot of Figure 5(a), it can be seen that by far the W3D to W4D range produced the highest NOx, approximately 590.338 ppm, shown by the red region ranging from 20% to 40% of engine loads. Strong evidence of reduction in NOx exhaust emissions was found when the engine was operating with W10D, which indicates that within that range, W10D yielded approximately 239.171 ppm of NOx, which was lower than the other fuel blends by 26.85% to 59.49%. The reductions in NOx exhaust emissions observed to occur with increasing of water.

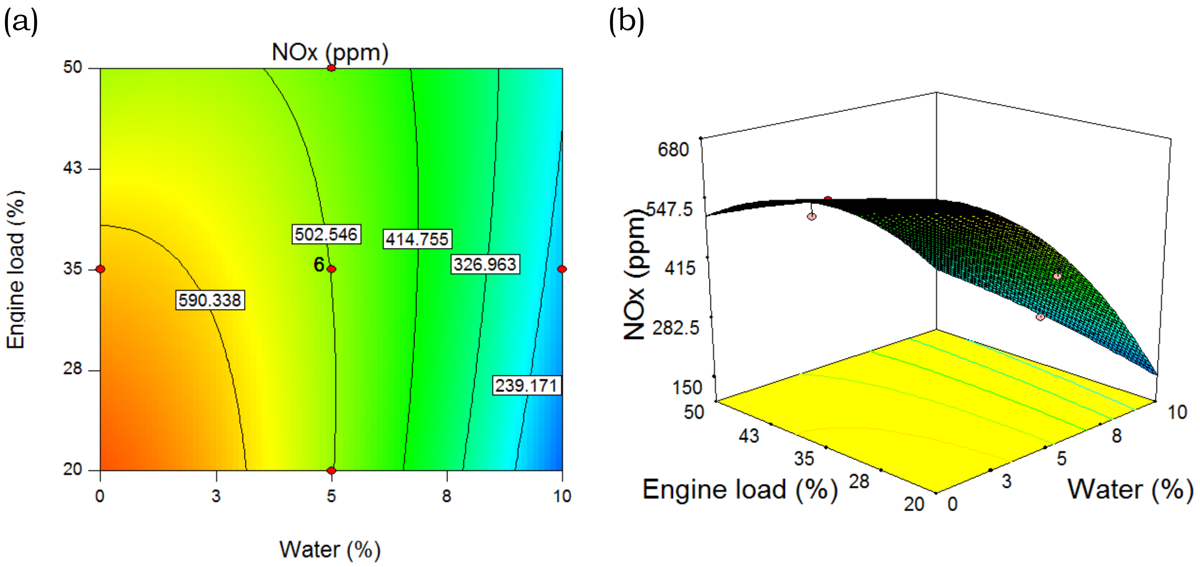

Figure 5 : Interactive plot for engine exhaust emissions of Nitrogen Oxide at different engine loads and fuel blends

Finally, the relation between NOx emissions with water (A), engine loads (B) and engine speed (C) mention in Eq. (4).

$$NOx = 868.72 - 28.59A - 11.95B - 4.49 \times 10^{-3}C + 0.87AB - 2.58 \times 10^{-3}AC + 5.28 \times 10^{-3}BC - 3.62A^2 - 0.06B^2 - 3.26 \times 10^{-5}C^2 \quad (4)$$

Carbon Monoxide Analysis

Figure 6 (a) and (b) demonstrates the contour and three-dimensional (3D) plot at 2000 rpm of engine speed of a quadratic model of engine exhaust emissions for CO for various engine loads and fuel blends. Commonly, CO is highly toxic and it is tasteless, colourless also odourless. The CO occurs from unfinished combustion when there is not enough oxygen to fully combust the entire carbon bond in the fuel to CO_2. It also implies that the chemical energy is forfeited. Eq. (5) showed relation between CO emissions with engine speed (A), water percentage (B) and engine speed (C).

$$CO = 1.9 - 0.07A + 0.05B - 1.10 \times 10^{-3}C \quad (5)$$

In Figure 6(b), the quadratic function graph point out that CO emission is increased with the increasing of engine loads, whereas in Figure 6(a) the CO emissions decreased with increasing fuel-water blends. A possible cause for this could be due to the increasing molecular mass corresponding to the increasing water percentage in the diesel fuels. (Balki et al., 2014) seized the opinion that decreases in CO emissions are owing to the carbon amount in the fuels as well as higher laminar flame speeds which mean the engine has restricted time for the combustion cycle to complete.

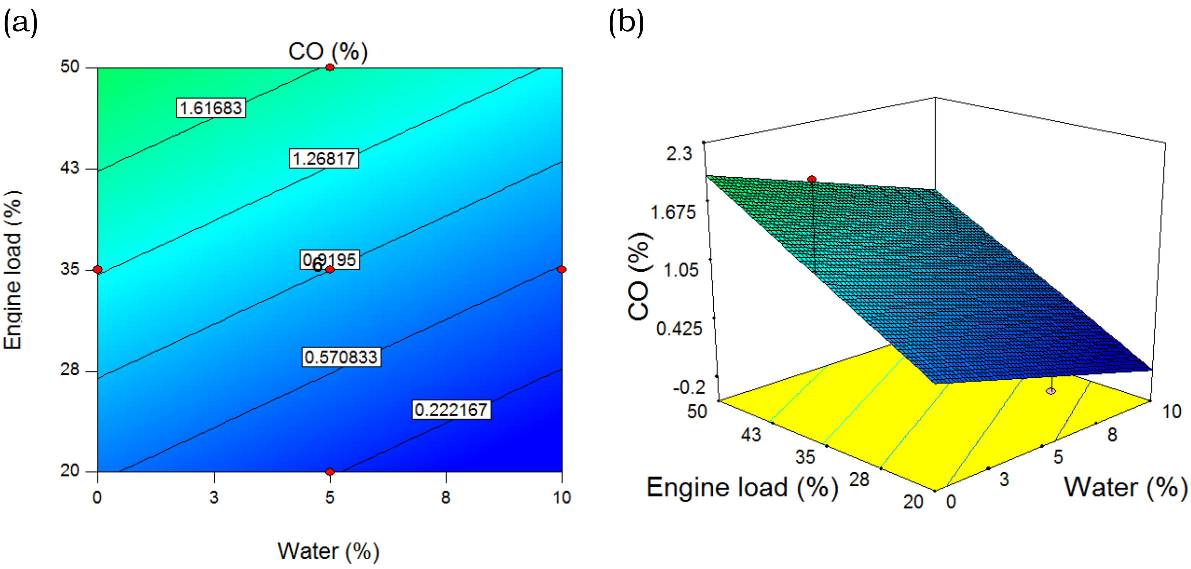

Figure 6 : Interactive plot for engine exhaust emissions of Carbon Monoxide at different engine loads and fuel blends

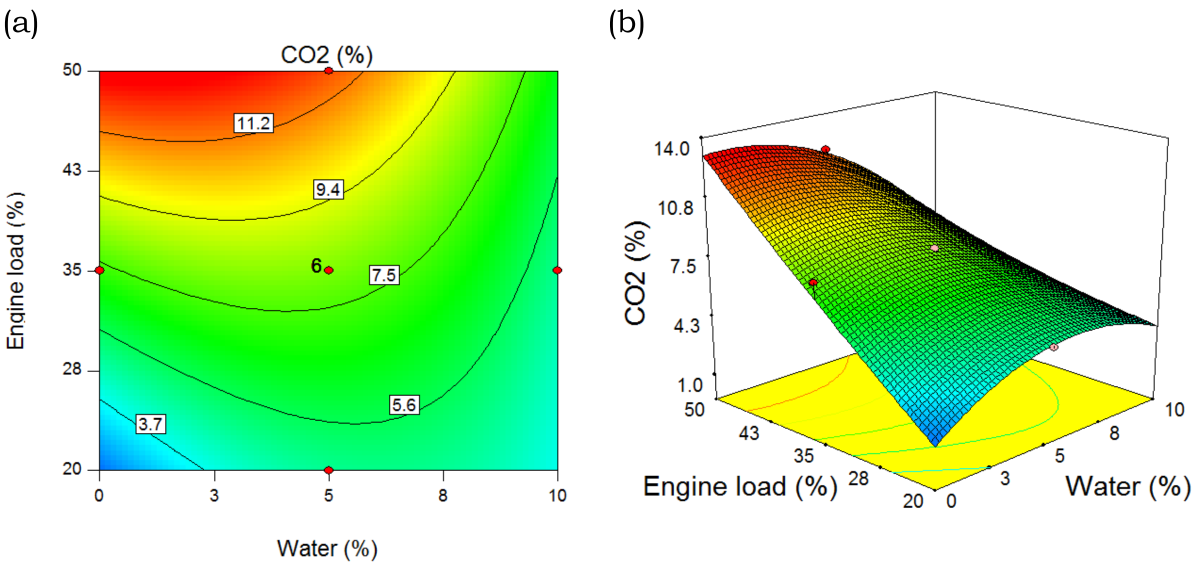

Figure 7 : Interactive plot for engine exhaust emissions of Carbon Dioxide at different engine loads and fuel blends

Carbon Dioxide Analysis

In Figure 7 the 3D interactive plot specifies that the CO_2 discharges in this engine produce a decreasing trend with the increased of water portion in fuel. Those results revealed that at a constant engine speed ranging from engine loads of 20% to 50%, CO_2 emissions were the highest specifically for 5% water in the gasoline fuels. The present findings seem to be consistent with other research which has also found that these increases in CO_2 emissions can be attributed to the extra oxygen in the water that allows partial reduction of the CO by forming into CO_2. Finally, the relation between CO_2 emissions with water % (A), engine load (B) and engine speed (C) mention in Eq. (6).

$$CO_2 = -5.23 + 1.70A + 0.17B + 2.76 \times 10^{-3}C - 0.03AB - 6.5 \times 10^{-5}AC + 7 \times 10^{-5}BC - 0.08A^2 + 9.5 \times 10^{-4}B^2 - 1.24 \times 10^{-6}C^2 \quad (6)$$

Optimization of Water Emulsion in Diesel

The process of optimization is governed by the desirability items in which its objective function lies between 0.0 and 1.0. The overall goal is essentially to obtain a combined desirability value for all of the factors and responses. The Ramp function graph of desirability for optimization of water-diesel emulsion, are presented in Figure 8. The importance of the responses can be varied from 1 to 5 that indicate the least to the most significant response, respectively. However, if the value of importance is the same for all of the responses, the value of the objective function will be reduced to the standard conditions for desirability. The idea of prophecy based on the criteria to conclude optimum performance and emissions characteristics. As of the desirability-based approach combination, only one best solution is obtained.

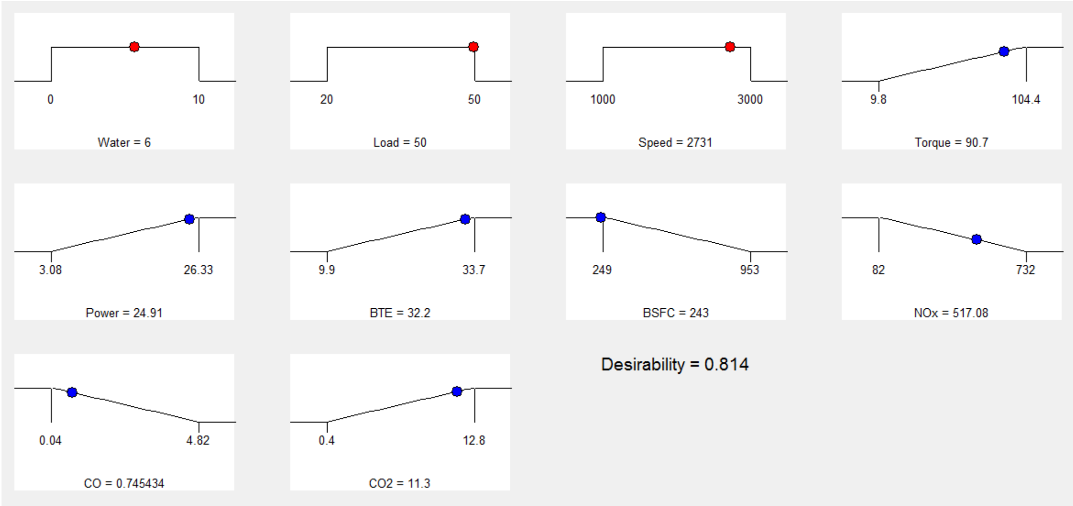

Figure 8: Ramp function graph of desirability for water in diesel emulsion optimization

A maximum desirability of 0.814 was found at the following input: 6 vol.% of water and 94 vol.% of diesel fuel (W5D) and at 2731 rpm of engine speed. This suggests that the best setting for all of the responses that does not conflict with each other was achieved at the aforementioned conditions. As for the optimum input parameters, the values of the brake power, BSFC, BTE, NOx, CO and CO_2 were found to be Figure 8. Interactive plot for engine exhaust emissions of carbon monoxides at different engine loads and fuel blends (a) contour plot and (b) 3D plot. 24.91 kW, 243 g/kWh, 517.08 ppm, 0.714 ppm and 51.3 ppm, respectively.

CONCLUSION

Base on the results of this study, the following conclusions are:

1. Performance characteristics indicated that adding a higher water proportion, of up to 10%, increased the brake power, and BFSC.
2. Exhaust emissions characteristics showed that the presence of water of up to 10% reduced the NOx, CO but yielded higher CO_2.
3. A high value 0.814 of desirability for optimum exhaust emissions characteristics and engine performance was accomplished has proved that the desirability approach of response surface methodology was to be an effective optimization technique.
4. The solutions obtained using the desirability approach specified that the most optimum condition was at engine speeds of 2731 rpm and fuel blends of W6D.

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