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Performance, Exhaust Emissions and Optimization Using Response Surface Methodology of a Water in Diesel Emulsion on Diesel Engine

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ABSTRACT

The use of water in diesel is an alternative to counteracting the increase in nitrogen oxide (NOx) emissions from diesel engines. However, some other criteria such as combustion performance and thermal efficiency were slightly reduced due to the impact of water content in diesel fuel. In other words, optimizing the balance between engine performance and emissions has always been a major problem in automotive industries. The purpose of this article is to demonstrate the use of RSM (response surface methodology) to improve the performance and emissions of a compression ignition (CI) engine which works on 5%, and 10% water mixes dubbed WD5 and WD10. This mixture of water emulsion to diesel is produced by using emulsifier ultrasonic. Tests were then performed on the Isuzu 4JJ1 4-cylinder 3000cc test bed engine with water cooled. Changes to engine load 20% to 50% and speeds of 1000rpm to 3000rpm. Experimental results data is then included in the Design Expert software to analyze the performance, emissions and optimization values using CCD Techniques in RSM. In performance analysis, pure diesel and WD5 are comparable with respect to power, heat efficiency of brakes and brakes of certain fuel consumption (BSFC). At higher loads, increased BTE levels and a neat BSFC drop were found. However, the combustion period is shorter. NOx and CO data slightly decreased with the same increase in water percentage at the same engine speed and load. However, the CO_2 data showed a sharp increase with the increase in water content in fuel. Optimum engine operating parameters found as 5% water ratio, 50% of load and 2446 rpm while the best output parameters found as 103.7 Nm. of torque, 26.3 kW power, 43.8% BTE, 172 g/kWh BSFC, 521.8ppm NOx and 3.1% of CO.

1. Introduction

At the moment, every part of the globe is concerned about the supply and environmental effect of fossil fuels. Given that fossil fuels are a non-renewable source of energy, their fast depletion and over-reliance on non-renewable energy must be addressed urgently [1-3]. Additionally, the use of

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these traditional energy sources, mostly in transportation, has resulted in significant environmental consequences [4-6]. The greenhouse gas emissions (GHGs), namely carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), and unburned hydrocarbon (HC), is of relevance because it influences the earth's climate [7,8].

As several studies have observed in the literatures, modifying the fuel by adding water to its container enables easy adjustment of performance and emissions. An emulsion is a combination of two or more liquids that cannot be mixed if one liquid contains an element of dispersion over another liquid. In other words, an emulsion is a special type of mixture made by combining two liquids that are not usually mixed [9]. There are several researchers reported that water in diesel can reduce NOx and smoke simultaneously. NOx emission decreased radically due to thermal, dilution and chemical effects (improvement of OH radicals) of water [10].

Numerous public health studies have shown that diesel exhaust has long-term consequences that may result in respiratory issues, headaches, and a variety of respiratory-related disorders. To address this issue, many forms of alternative fuels have been utilised in replacement of petroleum-based fuels. There are several sorts of fuels, including solid, liquid, and gaseous. In steam engine combustion chambers, solid fuels such as biomass and coal are often employed. Biodiesel, fat, and alcohol are all examples of liquid fuels. Meanwhile, gas fuels such as compressed natural gas (CNG), hydrogen (H_2), and biogas are increasingly common. Numerous studies on gasoline are popular among researchers because they do not involve any physical modifications to the engine, as other approaches do.

Jin *et al.,* [11] has reported the effects of water content on the solubility between several blended diesel fuel under various ambient temperatures. They used Isopropanol-Butanol-Ethanol as alcohol base to carry some water during fermentation process. Saleh [12] used diesel-biodiesel-butanol in their research. They investigated that butanol is one of the alternative fuels that can add oxygen to diesel engines. It is because the oxygen content of butanol is 21.6%. Butanol has advantages here due to its high heating value, high cetane number, low vapor pressure and good solubility. As a result of its increased solubility in diesel fuel, the use of butanol in diesel helps to alleviate the issue of fuel instability at low temperatures. The effects of different ratios of butanol in diesel fuel have been analysed in this study project based on the reasons mentioned.

Hence, in the present investigation an attempt has been made to use water-diesel emulsion as an alternative fuel in diesel engine. However, since the addition of emulsified water to diesel in diesel engines increases CO_2 emissions, various strategies such as varying the proportion of water in the diesel emulsion, engine speed, and engine load have been explored. In this study, the performance and exhaust emission characteristics of a DI diesel engine with response surface methodology (RSM) using water in diesel emulsion as alternate fuel have been determined and compared with pure diesel.

2. Methodology

2.1 Fuel Preparation

Two types of fuels were used during the engine testing. The first fuel was mineral diesel procured from a commercial petrol station, and the second fuel was blended emulsified water in-diesel, which water provide from distilled water for shell brand battery use. During the experimental study, emulsified water in diesel blend fuels were labelled as WXD, where (X) signifies the volumetric blending percentage of water mixed with mineral diesel. In this study the blended fuel used were W5D and W10D as shown in Figure 1. The detail table representation of the preparation of base diesel and water-diesel is depicted in Table 1. Initially, the importance of the surfactant was investigated for the preparation of the water in diesel 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 1
Details of test fuels

No.	Water-diesel blended fuel	Diesel (%) by vol.	Water (%) by vol.	Surfactants Span 80 (%) by vol.	Tween 80 (%) by vol.
1	D	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 diesel-butanol emulsion fuel. The details of surfactants with a mixture of Span80 and Tween80 and their proportions are tabulated in the Table 4 and Table 5. Fuel beaker and laboratory overhead paddle stirrers are utilized to prepare the stable WDBu 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 Awang and May [13], 2% of surfactant is the best mixing for emulsion fuel. After the agitation, both the surfactants mixed thoroughly and kept in a separate container.

Fig. 1. Sample preparation

The magnitude of Hydrophilic-Lipophilic Balance (HLB) between the two surfactants indicates the relative strength of the hydrophilic and lipophilic and the emulsion stability. The combined HLB value for the two surfactants is estimated using the equation [14]:

$$HLB_{AB} = [(H_A \times W_A) + (H_B \times W_B)]/(W_A \times W_B) \tag{1}$$

Where HA, HB, WA and WB denote the HLB values and weights of the two surfactants, Span80 and Tween80 respectively. It was found that the HLB value of 10 produced most stable water in diesel emulsion fuel. All the tested fuels were prepared of the same value of HLB.

2.2 Engine Setup

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 2. The engine performance laboratory of the Faculty of Mechanical Engineering at Universiti Malaysia Pahang was utilized to conduct this investigation. The different components of the experimental engine test rig are shown. The diesel engine used in this study is a turbocharger, water cooled, Isuzu 4JJ1 diesel engine. The AIC fuel flow meter is used to connect stainless steel fuel tanks with 10 liters of capacity. Stainless steel tubing is used to deliver the fuel from the fuel tanks to the engine fuel injection system. The fuel supply changes to the desired fuel tank using ball type valves that are connected to the fuel tubing. The fuel flow data were displayed in real time to a board computer model type BC-3033. The temperature of the fuel at the inlet and outlet of the fuel rail is measured by two K-type thermocouples to ensure a suitable fuel temperature of the returned fuel. The air intake system (Meriam 50MY15-6F) from Scott Peter Company was used to create laminar intake air flow to the engine. Intake air is supplied from the air intake filter to the engine manifold. The pressure drop across the intake air elements is measured with an Airflow manometer. A KANE gas analyzer is used to conduct the measurements of the exhaust flue gases constituent such as CO, CO_2, O_2 and NOx.

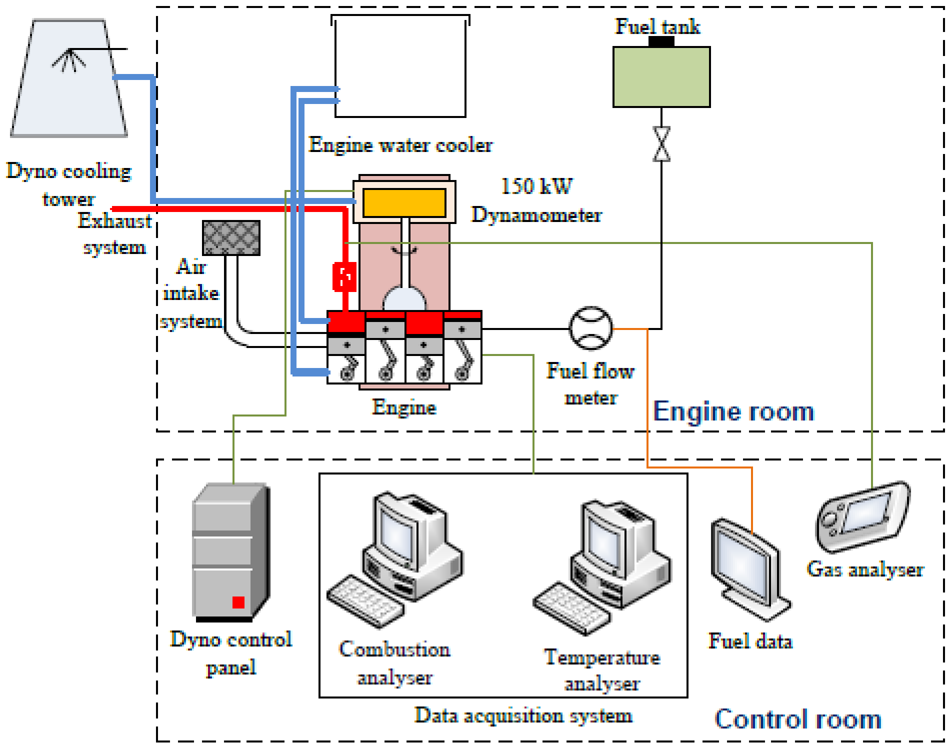

Fig. 2. Schematic diagram of the engine test rig

Table 1 shows the engine specifications and the engine characteristics curves respectively. This engine is equipped with an exhaust gas recirculation system; however, in this study the EGR mode is set to OFF. To ensure the consistency and the accuracy of the measurement data, the engine had been running approximately for five minutes with diesel fuel after completing the test then the fuel was changed for the next test.

Table 1
Isuzu 4JJ1 diesel engine specifications

Description	Specifications
Engine Model	ISUZU 4JJ1E4C-L
Type	Turbocharged, water cooled, overhead valve
Bore (mm)	95.4
Stroke (mm)	104.9
Displacement (L)	2.999 L
Number of cylinders	4 in-line
Compression ratio	17.5
Connecting rod length (mm)	150.0

2.3 Desirability Approach for Optimization

The optimization analysis can be carried out using Design Expert software, where each response is transformed to a dimensionless desirability value (d) and it ranges between d = 0, which suggests that the response is completely unacceptable, and d = 1 suggests that the response is more desirable. The goal of each response can be either maximize, minimize, target, in the range and/or equal to depending on the nature of the problem. The desirability of each response can be calculated by the following equations with respect to the goal of each response.

For a goal of minimum,

$$d_i = 1\ when\ Y_i \le Low_i;\ d_i = 0\ when\ Y_i \ge high_i;\ and \tag{2}$$

$$d_i = [\frac{high_i - Y_i}{high_i - low_i}]^{wti} when\ low_i < Y_i < high_i \tag{3}$$

For a goal of maximum,

$$d_i = 0\ when\ Y_i \le Low_i;\ d_i = 1\ when\ Y_i \ge high_i;\ and \tag{4}$$

$$d_i = [\frac{Y_i - low_i}{high_i - low_i}]^{wti} when\ low_i < Y_i < high_i \tag{5}$$

For target of target,

$$d_i = 0\ when\ Y_i \le Low_i;\ Y_i \ge high_i \tag{6}$$

$$d_i = [\frac{Y_i - low_i}{T_i - low_i}]^{wt1i} when\ low_i < Y_i < T_i \tag{7}$$

$$d_i = [\frac{Y_i - high_i}{T_i - high_i}]^{wt2i} when\ T_i < Y_i < high_i \tag{8}$$

For goal within the range,

$$d_i = 1\ when\ low_i < Y_i < high_i \tag{9}$$

$$d_i = 0;\ \text{for otherwise} \tag{10}$$

where

"*i*" is response,
"*Y*" is value of response,
"*low*" is lower limit of the response,
"High" is upper limit of the response,
"*T*" is target value of the response,
"*wt*" is weight of the response.

The shape of the desirability function can be changed for each response by the weight field. Weights are used to give more emphasis to the lower/upper bounds. Weights can be ranged from 0.1 to 10; a weight greater than 1 gives more emphasis to the goal, weighs less than 1 give less emphasis. When the weight value is equal to one, the desirability function varies in a linear mode. Solving of multiple response optimizations using the desirability approach involves a technique of combining multiple responses into a dimensionless measure of performance called the overall desirability function, D ($0 \leq D \leq 1$), is calculated by

$$D = \left(\prod_{i=1}^{n} d_i^{ri}\right)^{1/\sum ri} \quad (11)$$

In the overall desirability objective function (*D*), each response can be assigned an importance (*r*), relative to the other responses. Importance varies from the least important value of 1, indicated by (+), the most important value of 5, indicated by (+++++). A high value of *D* indicates the more desirable and best functions of the system which is considered as the optimal solution. The optimum values of factors are determined from value of individual desired functions (*d*) that maximizes *D*.

3. Results

Figure 3 shows that there is a steady increase of brake torque and power with respect to water to diesel percentages respectively at 50% of load. The configuration of the engine speed ranges from 1000 rpm to 3000 rpm. Whereas the percent configuration of the water in diesel emulsified fuel ranges from 0% to 10%. We can see that, water percentages with 5% to diesel (W5D) resulted in the highest engine brake power across all engine speeds compared to other fuels. Furthermore, according to the contour plot in Figure 3, W5D achieved a higher engine brake torque of 108.3 Nm at lower engine speed in comparison to other percentages of emulsified blended fuels at same level of speed. This is normal with turbocharger type engines because it produces high air intake pressure. This condition allows for strong combustion energy production at the early of the speed. The thing that attracted attention was that the high torque arches occurred at a water content of less than 9% at speeds of less than 2000rpm.

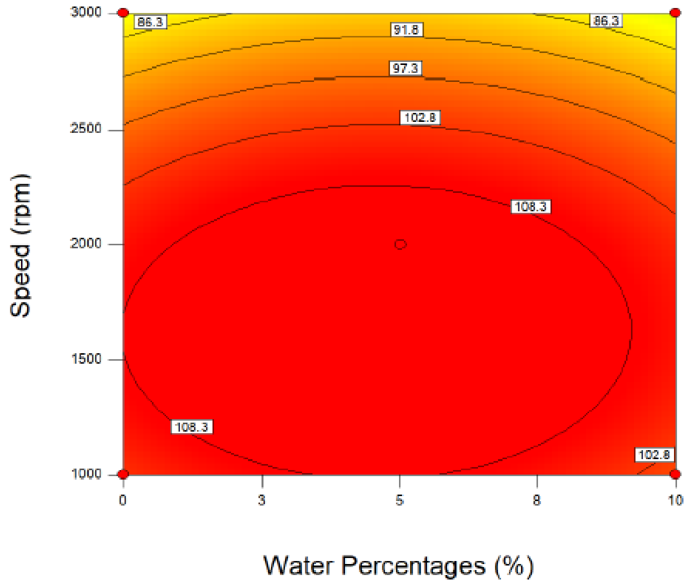

Fig. 3. Interactive contour plot for engine torque at difference percentages of water and speed

Figure 4 shows the interactive contour plot for brake thermal efficiency (BTE) at difference percentages of water and load of 50%. The figure clearly shows that the optimal area of BTE occurs at the content of water in-diesel about 1% - 8% and the engine speed of 1700 rpm and up to 3000 rpm, the value of BTE reaches up to 40.2%. However, at low engine load, the BTE rate began to decrease. This reduction occurs significantly in all range of water content percentages but decreased sharply when the water content was more than 8%. A good BTE reading rate at a water content range of 1% - 8% indicates excellent fuel combustion even on middle engine speeds. This can be described as follows. Although the lower heating value of emulsified blended diesel fuel smaller than diesel fuel, because of the high oxygen content, especially in the rich air fuel mixture points to provide better combustion and due to the higher viscosity. Similarly, BTE increases with the rising engine load from 45% onward. On the other hand, it proves BTE increase with the increasing injection pressure.

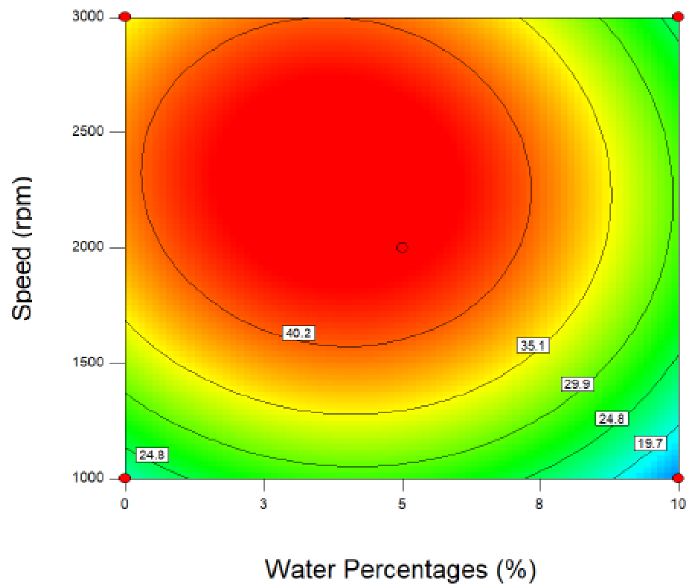

Fig. 4. Interactive contour plot for BTE at difference percentages of water and speed

Thermal efficiency is usually inversely proportional to fuel consumption. Figure 5. shows the interactive contour plot for brake specific fuel consumption (BSFC) at difference percentages of water and load of 50%. In the diagram, a semicircular oval-like contour appears to the BSFC's variation in the percentage of water in-diesel content and the percentage of load charged to the engine. The low BSFC value indicates better reading. It occurs at the border of 208 g/kWh within water content less than 6%. The graph also shows a high percentage of water content has increased the rate of BSFC. This statement coincides with the Figure 3 above which states BTE is reduced by the increase in water content in fuel.

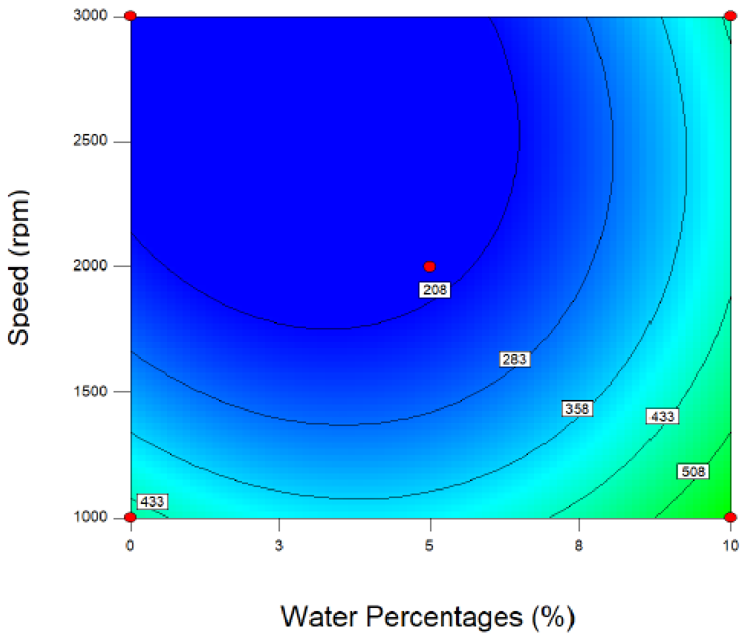

Fig. 5. Interactive contour plot for BSFC at difference percentages of water and speed

The overall effect of water ratio and engine speed on exhaust emissions are presented in Figure 6 to Figure 9. In the combustion process, the fuel mixes with the outside air that goes into the cylinder. Although the air content has an element of oxygen, it also contains nitrogen elements up to 78%. When the combustion temperature is too high that exceeds 1100 °C, oxygen will become reactive to act with nitrogen to form nitrogen oxides. In theory, the oxygen contained in emulsified fuels will increase amount of combustion especially in rich oxidation areas. Therefore, the in-cylinder temperature and NOx amount also increase increased. This is clearly shown in Figure 6. In the figure below, there is an NOx value contour that goes through the percentage of engine speed graph against the percentage of water content. It was found that the engines speed was inversely proportional to the increase in water content in diesel. But at the same percentage rate of water content, NOx increases with increased engine speed. Commonly known, when the engine speed increases, the content of injection of fuel and air into the cylinder is increased. This causes the combustion rate to become greater and then causes the in-cylinder temperature to increase. Indirectly NOx also increases. Conversely, as the amount of combustion decreases with increasing the water content ratio, the internal cylinder temperature and thus NOx amount increase at the same engine speed case.

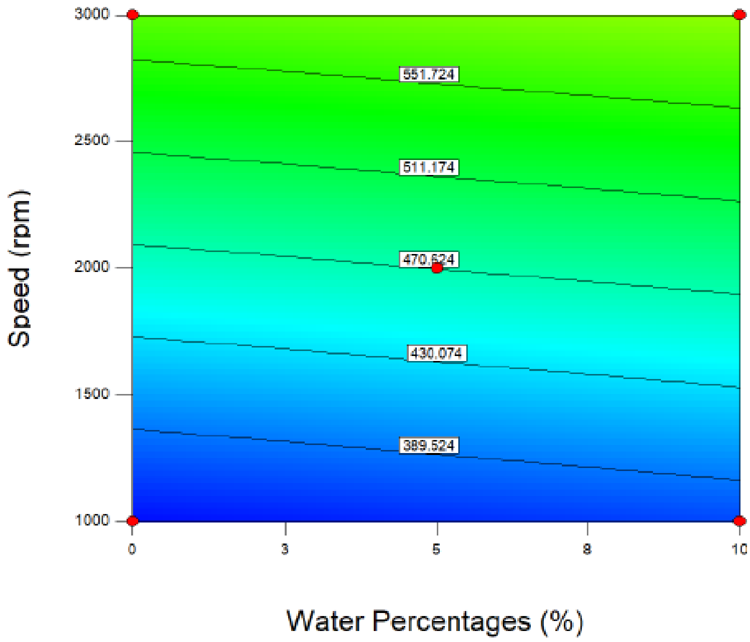

Fig. 6. Interactive contour plot for NOx at difference percentages of water and speed

In addition, carbon monoxide is also taken into account in the analysis. Figure 7 shows Interactive contour plot for CO at difference percentages of water and speed between 1000 rpm to 3000 rpm. It was found that the line contour indicates that it is shrinking with an increase in water content. In other words, CO values are directly proportional to low speed but inversely proportional at high speed. Nevertheless, the thing to note is the value of the CO itself. It decreases with an increase in speed at the same rate of water content. This condition indicates more perfect combustion at high speed due to the phenomenon of micro-explosion in the water content. Therefore, the formation of CO can be reduced [15].

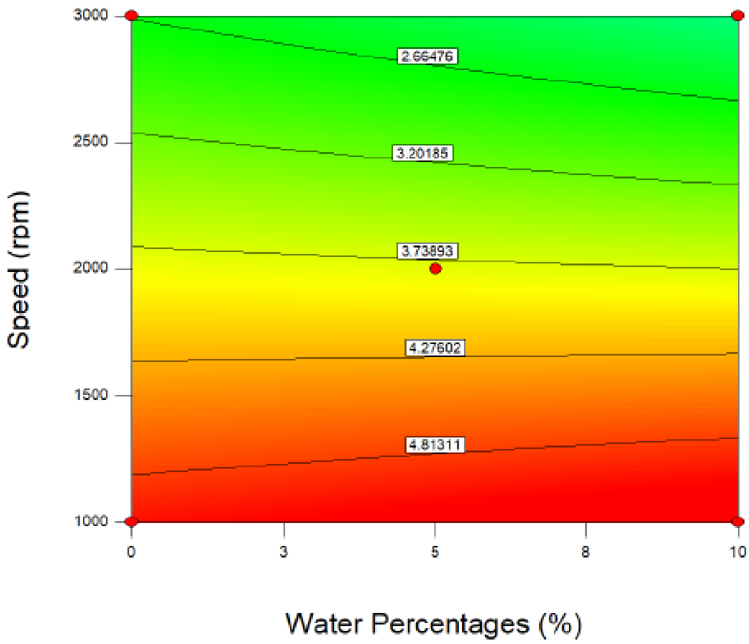

Fig. 7. Interactive contour plot for CO at difference percentages of water and speed

Moreover, with the increase in speed from 1000 rpm to 3000 rpm, the CO_2 increased as seen in Figure 8. In addition, the oxygen content from the water increased the amount of oxidation in the cylinder by providing the exceed required amount of oxygen in the combustion areas and increase CO_2. The increase in CO_2 is directly proportional between speed and water content in diesel fuel. The highest line of CO_2 content in emissions is 14% at speeds above 2500 rpm.

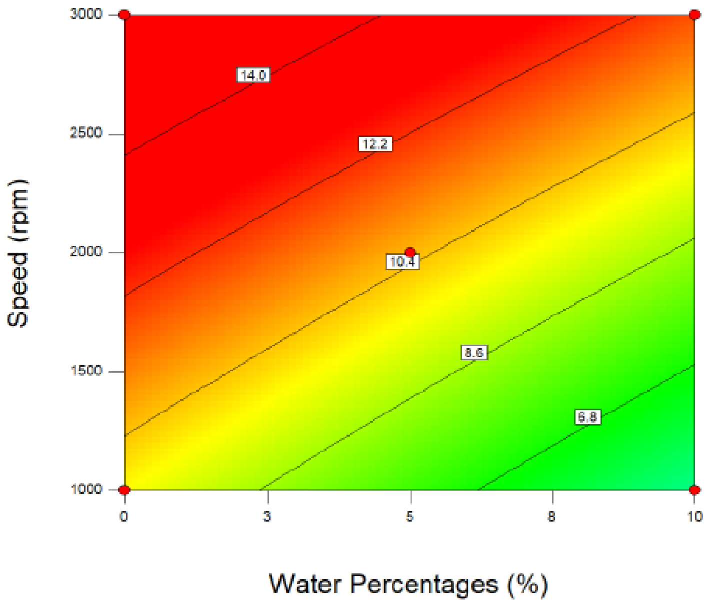

Fig. 8. Interactive contour plot for CO_2 at difference percentages of water and speed

In this study, the RSM optimizer is applied to optimize the engine load, engine speed and water to diesel ratio as the engine operating parameters and to achieve the best output factors according to the optimized operating factors. Table 2 shows the optimization constraints setting for emulsified water to diesel. While trying to achieve the highest level of engine efficiency, on the other hand, it has been tried to keep emissions to a minimum level.

Table 2
Constraints setting for emulsified water to diesel optimization

Name	Goal	Lower Limit	Upper Limit
Water	is in range	0	10
Load	is in range	20	50
Speed (RPM)	is in range	1000	3000
Torque (Nm)	maximize	9.8	107.5
Power (kW)	maximize	3.1	26.3
BTE (%)	maximize	9.9	43.1
BSFC (g/kWh)	minimize	206.2	952.7
NOx (ppm)	minimize	343	732
CO (%)	minimize	0.28	5.11
CO_2	is in range	0.4	12.8

The solution found for emulsified water to diesel optimization are shown in Table 3. According to the results, optimum engine operating parameters found as 5% water ratio, 50% of load and 2446 rpm while the best output parameters found as 103.7 Nm. of torque, 26.3 kW power, 43.8% BTE, 172 g/kWh BSFC, 521.8ppm NOx and 3.1% of CO. Figure 9 shows the model graph for emulsified water to diesel optimization. The conditions on the figure show the W5D at speed 2446 rpm and the load is 50% in the best position. As such, W5D samples were selected for the experiment alongside butanol as an additive to measure the impact on diesel engine performance, emissions and stability.

Table 3
Solution found for emulsified water to diesel optimization

Number	Water	Load	Speed	Torque	Power	BTE	BSFC	NOx	CO	Desirability	
1	5	50	2446	103.7	26.3	43.8	172	521.8	3.1	0.773	Selected
2	5	50	2446	103.7	26.3	43.8	171	521.8	3.1	0.773	
3	5	50	2447	103.7	26.3	43.6	175	522.1	3.1	0.773	
4	5	50	2447	103.7	26.3	43.8	170	521.8	3.1	0.773	
5	5	50	2411	105	26.3	44.3	167	517.1	3.2	0.773	

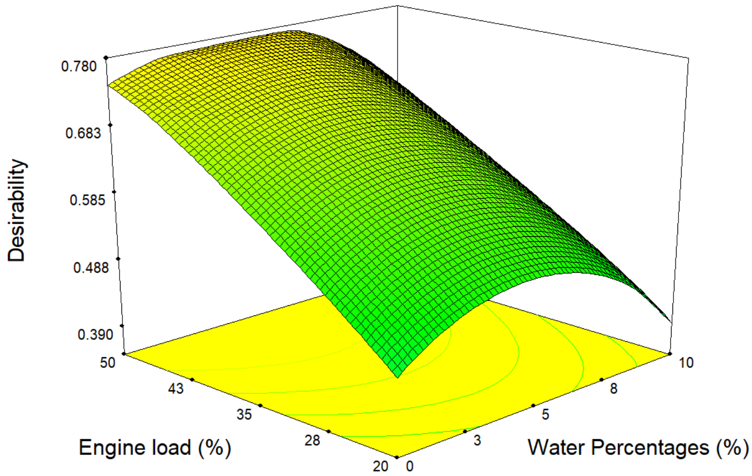

Fig. 9. Model graph for emulsified water to diesel optimization

4. Conclusions

Overall, the RSM optimization technique can be used for any combination of fuel blend of interest in determining the best blend ratios for engine performance and exhaust emissions parameters. This experimental design considerably reduced the time required by minimizing the number of experiments to be performed and provided. The main conclusions are summarized as follows

i. A higher engine brake torque of 108.3 Nm applies at lower engine speed and lower percentages of emulsified blended fuels at same level of speed.
ii. The optimal area of BTE occurs at the content of water in-diesel about 1% - 8% and the engine speed of 1700 rpm and up to 3000 rpm. The value of BTE reaches up to 40.2%.
iii. The low BSFC value occurs at the border of 208 g/kWh within water content less than 6%.
iv. NOx was found that the engines speed was inversely proportional to the increase in water content in diesel. But at the same percentage rate of water content, NOx increases with increased engine speed.
v. With increasing of water content, CO values are directly proportional to low speed but inversely proportional at high speed of engine.
vi. The increase in CO_2 is directly proportional between speed and water content in diesel fuel.
vii. Optimum engine operating parameters found at 5% water ratio, 50% of load and 2446 rpm while the best output parameters found as 103.7 Nm. of torque, 26.3 kW power, 43.8% BTE, 172 g/kWh BSFC, 521.8ppm NOx and 3.1% of CO.

viii. The conditions on the testing show the W5D at speed 2446 rpm and the load is 50% in the best position of optimization in this study.

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