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RESEARCH ARTICLE

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Performance and emission characteristics of a diesel engine operating on different water in diesel emulsion fuels: optimization using response surface methodology (RSM)

Abstract The nitrogen oxide (NO_x) release of diesel engines can be reduced using water in diesel emulsion fuel without any engine modification. In the present paper, different formulations of water in diesel emulsion fuels were prepared by ultrasonic irradiation. The water droplet size in the emulsion, polydisperisty index, and the stability of prepared fuel was examined, experimentally. Afterwards, the performance characteristics and exhaust emission of a single cylinder air-cooled diesel engine were investigated using different water in diesel emulsion fuels. The effect of water content (in the range of 5%–10% by volume), surfactant content (in the range of 0.5%–2% by volume), and hydrophilic-lipophilic balance (HLB) (in the range of 5–8) was examined using Box-Behnken design (BBD) as a subset of response surface methodology (RSM). Considering multi-objective optimization, the best formulation for the emulsion fuel was found to be 5% water, 2% surfactant, and HLB of 6.8. A comparison was made between the best emulsion fuel and the neat diesel fuel for engine performance and emission characteristics. A considerable decrease in the nitrogen oxide emission (–18.24%) was observed for the best emulsion fuel compared to neat diesel fuel.

Keywords water in diesel emulsion fuel, hydrophilic-lipophilic balance (HLB), response surface methodology (RSM), emulsion stability, engine performance, exhaust emission

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1 Introduction

Diesel engines can be considered as economical and efficient power sources for various applications including construction, transportation, and agricultural segments. The main fuel of these engines is the neat diesel fuel obtained from crude oil refining. Using diesel as a fossil fuel leads to the emission of greenhouse gasses and particulate matters (PM) which threatens public health and environment. Combustion of fossil fuels results in the production of different gasses such as carbon monoxide (CO), carbon dioxide (CO_2), unburnt hydrocarbon (UHC), and nitrogen oxides (NO_x) which are the main factors of environment pollution. Depletion of fossil fuels resources, increment in energy requirements, and environmental concerns have made it necessary for researchers to seek for replacement of fossil fuels with alternative fuels sources. Water in diesel emulsion fuel is as an attractive alternative for the improvement of engine performance and reduction of harmful emission. The application of emulsion fuels can lead to an increment in the thermal efficiency. Micro-explosion phenomenon is associated with the combustion of emulsion fuels. In this process, the size of fuel droplets is decreased as a result of expansion of water due to heating in the combustion chamber. The rapid expansion of the water droplet causes secondary atomization which, in turn, leads to complete combustion. As a result, more complete combustion is achieved in the engine and the emission of gases such as CO and UHC, which are the result of incomplete fuel combustion, is decreased. The injection of water into the diesel engine results in a decrease in the emission of soot and particulate matters, as well. Numerous studies have been accomplished in order to examine the engine performance using emulsion fuels. Seifi et al. [1] have studied the influence of water content of the emulsion fuel on the torque and engine power by selecting water percentages of 2%, 5%, 8%, and 10% by volume and constant surfactant percentage of 2% by volume. According to their report, a remarkable decrease in the torque and power of engine is observed by increasing water content in the emulsion fuel. Mazlan et al. [2] have also studied the impacts of various water percentages (5%, 6.5%, 10.8% and 30%) in non-surfactant emulsion fuel on the performance and emissions of diesel engine. According to their report, the lowest fuel consumption and the highest average decrease of NO_x are observed for the emulsion fuel with a water percentage of 6.5%. According to Tan et al. [3], using the emulsion fuels results in the reduction of the brake power and torque of engine in comparison with diesel fuel. They have employed a combination of span 80 and tween 80 as surfactants with an HLB value of 11.67 at various diesel, biodiesel, and bioethanol ratio. Alahmer et al. [4] have also reported the torque reduction with increment in the water content of the emulsion fuels. According to Yang et al. [5], brake thermal efficiency of the engine is improved for all engine speeds. Moreover, Abu-Zaid [6] has reported a 3.5% enhancement in brake thermal efficiency for the emulsion fuel compared to the neat diesel fuel. Suresh and Amirthagadeswaran [7] have considered the proportion of water-in-diesel of 0%, 5%, and 10% and examined the performance characteristics in terms of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE). According to their report, BFSC and BTE are improved by an increment in the water content of emulsion fuel at various loads. Bidita et al. [8] have stated that the BSFC and exhaust mass flow rate is reduced significantly by using emulsion fuels compared to neat diesel. They have applied nanoemulsion with different values of water (0.7%–1% by volume) and surfactant (0.25%–0.4% by volume) with water droplet size in the range of 2 to 200 nm. Ithnin et al. [9] have investigated the specific fuel consumption (SFC) with varying water percentages (5% to 20% with 5% enhancement) and fixed surfactant percentage of 2% at different engine loads. They have figured out that the SFC of all water in diesel emulsions is improved compared to neat diesel. Basha et al. [10] have demonstrated that the application of emulsion fuel leads to an increase in BSFC, which is 0.35 and 0.33 kg/kWh for emulsion fuel and neat diesel, respectively. They have indicated that the BTE of the emulsion fuel is 26.9% in comparison with 25.2% for neat diesel. Ogunkoya et al. [11] have reported the significant enhancement of BSFC and BTE using emulsion fuels in comparison with their base fuels. Alahmer [12] has determined the water volumetric percentage range between 0%–30% and observed the highest BSFC and the lowest torque and thermal efficiency at water volumetric percentage of 5%. Attia et al. [13] have showed that the smaller droplets in the emulsified fuel has a more pronounced efficacy on the engine performance. Yang et al. [14] have reported that the nano-sized water droplets in the emulsion fuel under the influence of the micro-explosion phenomenon can accelerate the fuel vaporization and its mixing process with air, in turn, decreases the total combustion time. Ithnin et al. [9] have reported a decrease in the PM and NO_x release for the emulsion fuel comparing the neat diesel fuel. According to their report, the best performance regarding NO_x and PM emission is achieved for the emulsion fuel with water percentage of 20% and surfactant percentage of 2%. Henningsen [15] has reported a 30% decrease in the NO_x emission using water in diesel emulsion fuel with 25% of water. This result is in good agreement with the observations of Basha et al. [10] regarding NO_x emission and smoke opacity. Basha et al. [10] selected water percentage of 15% by volume and surfactant percentage of 2% by volume and observed NO_x emission reduction from 1340 ppm for neat diesel to 1009 ppm for the emulsion fuel. Nadeem et al. [16] have reported the greatest decrease in the emission of pollutants using emulsion fuel prepared with water content of 15%. Yang et al. [5] have demonstrated a reduction in the peak flame temperature using the emulsion fuel due to the presence of water which, in turn, decreases the NO_x emission. Ochoterena et al. [17] have reported an 81% and 89% reduction in PM emission for emulsion and micro-emulsion fuels, respectively. According to Alahmer et al. [4], a decrease in NO_x is observed by increasing the water content of emulsion fuels. They have also reported a higher CO_2 emission for the emulsion fuel in comparison with the neat diesel fuel. Attia et al. [13] have indicated that NO_x emission is decreased to 25% when large water droplets (i.e., 5.5 μm) are applied in the emulsion. Besides, the application of small water droplets (i.e., 0.53 μm) in the emulsion leads to a reduction of 80% and 35% in the smoke and unburned hydrocarbons, respectively. Regarding the CO and HC emission, Subramanian [18] has reported an increase in the emission for emulsion fuels in comparison with neat diesel but other researchers have reported contradictory results [8] and some researcher have reported no meaningful difference [5]. According to Lin et al. [19], the CO and CO_2 emission increase with engine load. Furthermore, Lin et al. [20] have reported an increase in CO and a decrease in NO_x release by the increment in the engine speed in the range of 1000–2200 r/min. Hegde et al. [21] have examined the impact of various surfactants on the emission of harmful gasses and found that the overall emissions are decreased influentially for the emulsion fuel in comparison with the neat diesel fuel when a constant ratio of tween 80 and span 80 is employed. Ramakrishnan et al. [22] have optimized the performance and exhaust emission variables of a kind of fuel blend based on the response surface methodology (RSM). They considered three factors of compression ratio (CR), load, and fuel blend composition. Vellaiyan et al. [23] have also presented a multi-purpose optimization for water-biodiesel emulsion fuel and nanoadditive, whose results demonstrate that the amount of water in the emulsion has the most impact on the performance and emission in a diesel engine. Other researchers [24–28] have conducted studies to investigate the influences of different additives on the performance and emission characteristics of diesel engines along with their benefits and disadvantages. In the recent decade, various papers have been published regarding diesel engine performance and the engine exhaust emission using emulsion fuels [29–41]. Table 1 summarizes previous studies which examine the impact of using different emulsion fuels on engine performance and exhaust emission.

RSM is a collection of mathematical and statistical techniques which can be applied for experimental design, construction of empirical model, and determination of appropriate operating conditions for target responses. In RSM, a polynomial equation is fitted to the experimental data to describe the relationship between the response of interest and several variables with the objective of evaluating the effects of independent variables, and their interaction effects. RSM can be applied in the optimization of operating parameters in combined systems [42].

It should be noted that a large number of researches has been devoted to this topic, but the results reported are conflicting. Besides, the simultaneous effect of water content, surfactant content, and hydrophilic-lipophilic balance (HLB) has not been investigated yet. Moreover, the stability of emulsion fuel is an important issue from a practical point of view. The dependence of stability of the emulsion fuel to water droplet sizes in the disperse phase and polydispersity index (PDI) has been rarely discussed. To the best of the authors' knowledge, a limited number of works have employed ultrasonic irradiation to prepare water in diesel emulsion fuels. These two items are rarely investigated along with engine performance and exhaust emission. Therefore, in-depth studies should be accomplished on the formulation of emulsion fuels considering the interactive effects of water and surfactant concentrations and the type of surfactants. The principal aim of this paper is to examine the influence of effective parameters of water percentage, surfactant percentage, and HLB value on the emulsion stability as well as the engine performance and exhaust emission and their interactions based on RSM (Box-Behnken design). Eventually, the optimization of the emulsion fuel formulation considering the engine performance and exhaust emission is conducted based on RSM.

2 Experimental

2.1 Material

The specifications of neat diesel used in the present paper are listed in Table 2. Two different surfactants including span 80 (hydrophobic) and tween 80 (hydrophilic) were used. The surfactants were purchased from Merck (Germany). The mixture of these surfactants was used to produce water in diesel emulsion fuels. The HLB values for span 80 ($C_{24}H_{44}O_6$) and tween 80 ($C_{64}H_{124}O_{26}$) are 4.3 and 15, respectively [43].

2.2 Emulsion fuel preparation procedure

In the present paper, a 400 W-20 kHz horn-type titanium (12 mm diameter) ultrasonic transducer (UTD 400 made by Ultrasound Technology Development Company, Iran) was used for the emulsification process. Emulsion fuels were produced using an ultrasound device in two stages. In the first stage, an appropriate amount of tween surfactant was mixed with certain amount of distilled water at ultrasound irradiation for 10 min to form a solution. In the second stage, the defined amount of span surfactant and neat diesel were added to the solution. Then, the blend was irradiated by ultrasound for 10 min. In both stages, the power of ultrasound was regulated to 300 W. Besides, 1 cm of the ultrasound probe was immersed into the mixture (Fig. 1). It should be noted that the required volume of water and surfactant was selected according to the Box-Behnken experimental design. The required amount of span 80 and tween 80 was selected in such a way to meet the suggested HLB by experimental design. The hydrophilic-lipophilic balance of mixed surfactants was determined by using Eq. (1).

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

where x_1 and x_2 are the mass fraction of surfactants in emulsion fuels, and H_1 and H_2 are the hydrophilic-lipophilic balance of each of the surfactants [44].

2.3 Engine test

A single cylinder air-cooled diesel engine was employed for the performance evaluation of water in diesel emulsion fuels. Detailed specifications of the employed diesel engine are presented in Table 3. The diesel engine was connected to an eddy current type DC dynamometer (±0.1 kW accuracy for power magnitude, ±0.1 N·m accuracy for torque magnitude, and ±1 r/min accuracy rotational speed magnitude) in order to measure the variables affecting the engine performance. The dynamometer created a magnetic field on the output shaft by motive force and recorded the reaction force. Afterwards, it calculated the necessary information such as torque, engine power, fuel consumption, and rotational speed through the electric sensors mounted on the engine. Besides, it had the software which controlled the test conditions. All setup operations and required adjustments of the diesel engine were controlled by the software.

To perform engine tests, the engine lubricating oil was changed before the experiments. In the first step, the prepared emulsion fuels with different quantities of water and surfactant, different HLB of surfactant were tested at a constant engine speed of 1800 r/min at full load. The

Table 1 A summary of the performance and emission characteristics of water in diesel emulsion fuels

Researcher's Name	Engine type and operating conditions	Characteristics of fuel composition	Surfactant Type	HLB value	Torque	Brake power	BSFC	BTE	CO	HC	CO_2	NO_x
Basha et al. [10]	One cylinder, Engine speed = 1500 r/min, Engine load = 100 %	Water = 15% (vol), Surfactant = 2% (vol)	Tween 80 and Span 80	8	No information	No information	increase	increase	increase	increase	No information	decrease
Seifi et al. [1]	Six cylinders, Engine speed = 1400–1900 r/min, Engine load = 25%–100%	Water = 2%–10% (vol), Surfactant = 2% (vol)	Span 80	4.3	decrease	decrease	No information	No information	No information	No information	No information	No information
Bidita et al. [8]	Engine speed = 2600 r/min, Engine load = 50%	Water = 0.7%–1% (vol), Surfactant = 0.25%–0.4% (vol)	Triton X-100	-	No information	No information	No information	No information	increase	No information	decrease	decrease
Alahmer et al.[4]	Four cylinders, Engine speed = 1000–3000 r/min, Engine load = 100%	Water = 5%–30%(vol), Surfactant = 2% (vol)	Tween 20	16.7	decrease	decrease	increase	decrease	No information	No information	increase	decrease
Basha et al. [25]	One cylinder, Engine speed = 1500 r/min, Engine load = 100%	Water = 5% (vol), Surfactant = 2% (vol)	Tween 80 and Span 80	8	No information	No information	increase	increase	decrease	increase	No information	decrease
Ithnin et al. [9]	One cylinder, Engine speed = 3000 r/min, Engine load = 25%–100%	Water = 5%–20% (vol), Surfactant = 2% (vol)	Span 80	4.3	No information	No information	No information	No information	increase	No information	No different	decrease
Abu-Zaid [6]	One cylinder, Engine speed = 1200–3300 r/min, Engine load = 100%	Water = 5%–20% (vol), Surfactant = 2% (vol)	Tween 80 and Span 80	-	increase	increase	decrease	increase	No information	No information	No information	No information

Table 2 Specifications of neat diesel fuel

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

torque, power, and specific fuel consumption of the diesel engine were obtained using the eddy current dynamometer. Then, the amount of brake power was calculated using Eq. (2), where T and n are the torque and engine speed, respectively. Besides, in order to obtain the BSFC, the mass flow rate was determined by Eq. (3) using two parameters of power (P) and specific fuel consumption (SFC). After that, the BSFC was computed using Eq. (4). Finally, the brake thermal efficiency was obtained using Eq. (5) in which H_v is the calorific value of fuel. It is necessary to mention that the measurement of calorific heat value of the desired fuel was accomplished by a Gallenkamp bomb calorimeter with an accuracy of ±0.1%. In addition, an AVL DITEST GAS 1000 was applied to evaluate the effective variables of emission of pollutants. This device is able to determine the emission of CO, CO_2, HC, and NO values. The detailed specifications of the applied analyzer are listed in Table 4. This apparatus was connected to a computer via blue tooth to observe and record the emission of different pollutants using special software. The emission of each produced emulsion fuels was examined at a constant engine speed of 1800 r/min at full load. The schematic of the system used in the engine test is illustrated in Fig. 2.

$$P_b = \frac{2\pi Tn}{60000}, \tag{2}$$

$$\mathrm{SFC} = \frac{M_f}{P}, \tag{3}$$

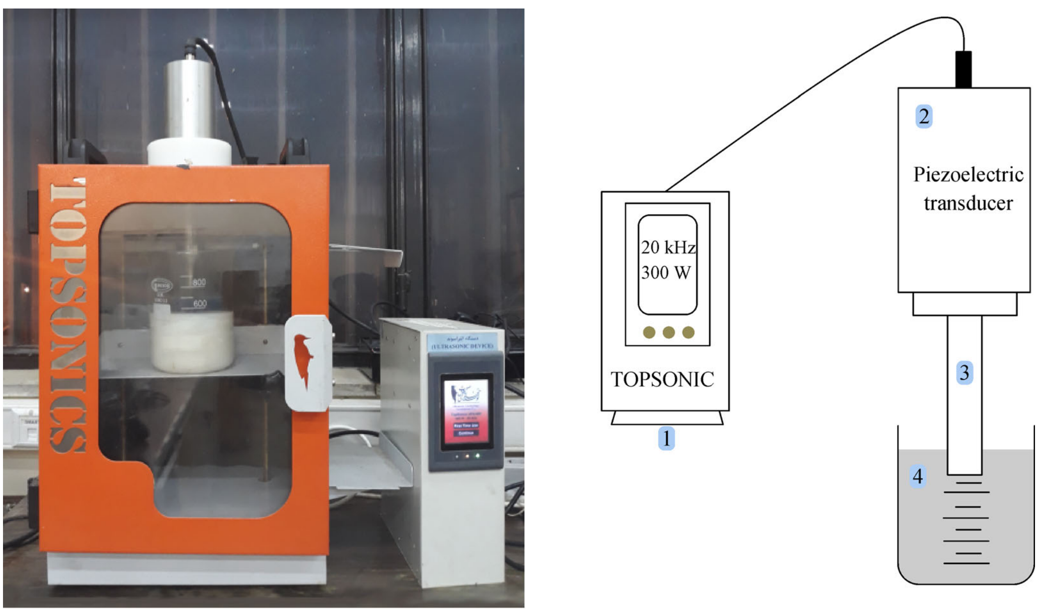
$$\mathrm{BSFC} = \frac{M_f}{P_b}, \tag{4}$$

$$\mathrm{BTE} = \frac{3600}{H_v \times \mathrm{BSFC}} \times 100\%. \tag{5}$$

It should be noted that the engine tests were conducted in the Renewable Energy laboratory, Bioenergy Research Center, Tarbiat Modares University, Tehran, Iran.

2.4 Box-Behnken experimental design

In this paper, RSM was employed to design and analyze the experiments. The influence of percentage of water, percentage of surfactant, and HLB on the variables of response (i.e., the torque, the brake power, BSFC, BTE, CO emission, HC emission, CO_2 emission, and NO_x emission) was investigated using RSM based on Box-



(a) (b)

1—generator, 2—transducer, 3—ultrasonic probe, 4—desired solution

Fig. 1 Experimental set-up for ultrasound-assisted emulsification process for production of emulsion fuels.

Table 3 Characteristics of applied diesel engine

Type	Lombardini-Diesel 3LD510
Number of cylinder	1
Swept volume	510 cm^3
Bore	85 mm
Stroke	90 mm
Compression ratio	17.5:1
Maximum torque at 1800 r/min	32.8 N·m
Maximum power at 3000 r/min	9 kW

Table 4 Detailed properties of AVL DITEST GAS 1000 emission analyzer

Variables	Measurement range	Measurement accuracy
CO	0%–15% (vol)	0.02% (vol)
CO_2	0%–20% (vol)	0.3% (vol)
HC	0–30000 ppm (vol)	4 ppm (vol)
NO	0–5000 ppm (vol)	5 ppm (vol)

Behnken design (BBD). In this step, the engine performance and the emission were evaluated in full load condition and 1800 r/min. The experimental range and factor level of the three influential parameters are tabulated in Table 5. According to BBD, 17 experimental runs are required, which includes five replicates of the central run. The BBD suggested experimental runs are given in Table 6. Equation (6) was employed to consider the influence of the independent variables and their interactions on the responses (i.e., the variables of engine performance and emission).

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\sum_{j=i+1}^{k}\beta_{ij}X_iX_j + \sum_{i=1}^{k}\beta_{ii}X_i^2 + \varepsilon. \tag{6}$$

In Eq. (6), Y is the predicted response of the engine performance and emission parameters (i.e., the torque, the brake power, BSFC, BTE, CO emission, HC emission, CO_2 emission, and NO_x emission); β_0 is the intercept coefficient (offset); β_i, β_{ij} and β_{ii} are the factors of linear, interaction, and quadratic terms, respectively; X_i and X_j are the coded independent parameters; and ε is the unanticipated error [42].

3 Result and discussion

3.1 Emulsion stability analysis

The stability of all prepared emulsion fuels was examined, visually. In this regard, the creation of the second phase was indicated as the onset of instability. In addition, the dynamic light scattering (DLS) method was applied for determination of the droplet size distribution to examine the quality of the emulsion fuel. The average hydrodynamic droplet size and poly dispersity index (PDI) were calculated using Nano ZS (red badge) ZEN 3600 made by Malvern Company (England). It was found that all emulsion fuels were stable at 25°C with a minimum stability of 12 h and a maximum stability of 216 h. Table 7 shows the results of stability analysis of the three samples with the lowest stability, the highest stability, and the most

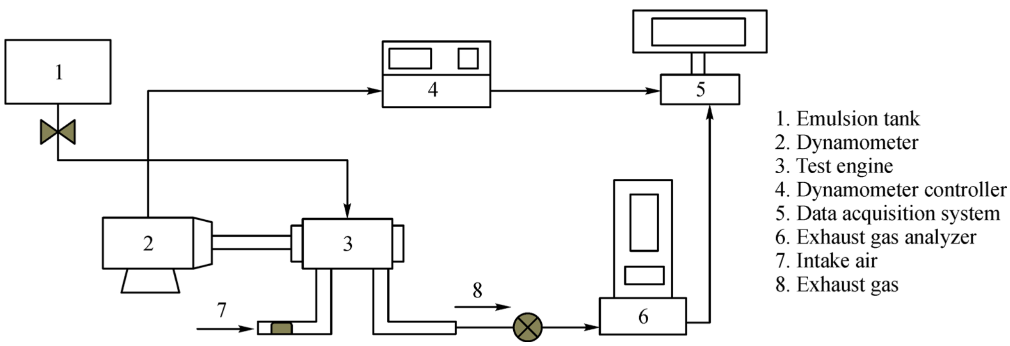


Fig. 2 Schematic of experimental set-up applied in engine test.

Table 5 Experimental ranges and factor levels of variables applied in the experimental design

Independent parameters	Range and levels		
	–1	0	+ 1
x_1: Percentage of water/%(vol)	5	7.5	10
x_2: Percentage of surfactant/%(vol)	0.5	1.25	2
x_3: HLB value	5	6.5	8

Table 6 Experimental runs suggested by BBD

Run	Coded values			Real variables		
	x_1	x_2	x_3	Percentage of water/%(vol)	Percentage of surfactant/ %(vol)	HLB value
1	0	0	0	7.5	1.25	6.5
2	+1	+1	0	10	2	6.5
3	0	+1	+1	7.5	2	8
4	–1	+1	0	5	2	6.5
5	+1	–1	0	10	0.5	6.5
6	–1	0	+1	5	1.25	8
7	0	–1	+1	7.5	0.5	8
8	0	0	0	7.5	1.25	6.5
9	+1	0	–1	10	1.25	5
10	0	0	0	7.5	1.25	6.5
11	0	+1	–1	7.5	2	5
12	0	–1	–1	7.5	0.5	5
13	0	0	0	7.5	1.25	6.5
14	–1	–1	0	5	0.5	6.5
15	+1	0	+1	10	1.25	8
16	–1	0	–1	5	1.25	5
17	0	0	0	7.5	1.25	6.5

Table 7 Stability analysis of emulsion fuel

Run	Real variable			Average droplet size/nm	PDI	Stability/h
	x_1	x_2	x_3			
1 (The BBD most repeated)	7.5	1.25	6.5	503.4	0.413	168
4 (The highest stability)	5	2	6.5	373.5	0.266	216
15 (The lowest stability)	10	1.25	8	676.5	0.485	12

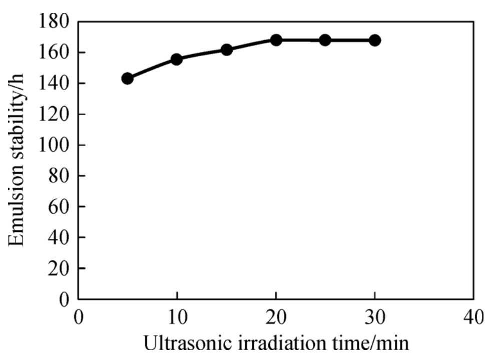


Fig. 3 Effect of emulsification time on stability of emulsion fuel for most repeated BBD experimental run.

repeated emulsion fuel in the BBD. The results of the measurements indicate that the average of droplet size is in the range of 373.5 to 676.5 nm. As can be seen, the stability of emulsion fuels enhances with decrement of the average droplet size. Furthermore, the effect of emulsification time on the stability of the emulsion fuel was investigated. For this purpose, the most repeated sample of BBD were tested at different emulsification times in the range of 5 to 30 min. The experimental results are illustrated in Fig. 3. As can be observed, the emulsion stability is increased significantly with the increment in emulsification time from 5 to 20 min. However, the stability duration of the emulsion fuel remains constant for the emulsification time beyond 20 min. Besides, the reported values for the stability of emulsion fuels in various studies are compared in Table 8.

3.2 Statistical analysis

The RSM proposed a correlation for each response (i.e., torque, brake power, BSFC, BTE, CO emission, HC emission, CO_2 emission, and NO_x emission) with the percentage of water, the percentage of surfactant, and HLB of surfactant. Table 9 shows the proposed correlations in terms of real parameters. In Table 9, Y is the response and x_1, x_2, and x_3 are the percentage of water, the percentage of surfactant, and HLB, respectively. The experimental results for BBD suggested runs, and predicted responses are given in Table 10.

Table 8 Reported values of emulsion fuel stability in various studies

Reference	Emulsion fuel characteristic	Surfactant type	Emulsification time/ min	Stability duration
Hasannuddin et al. [45]	20% water (vol) 1% surfactant (vol)	Span 80	5	75 min
Bidita et al. [8]	1% water (vol) 0.4% surfactant (vol)	Triton X-100	10	16 days
Ghannam et al.[46]	10% water (vol) 0.2% surfactant (vol)	Triton X-100	2	4 weeks
Patil et al. [43]	10% water (vol) 5% surfactant (vol)	Span 80 and tween 80	20	30 days
Noor El-Din et al. [44]	5% water (vol) 10% surfactant (vol)	Span 80 and tween 80	5	2 weeks

Table 9 Final correlations for variables of response in terms of real factors

The response	Correlation
T	$Y_T[\mathrm{N\cdot m}] = 16.942 + 0.153x_1 + 0.355x_2 + 0.784x_3 + 1.333 \times 10^{-3}x_1x_2 + 0.01x_1x_3 - 4.444 \times 10^{-3}x_2x_3 - 0.023x_1^2 - 0.171x_2^2 - 0.063x_3^2$
P_b	$Y_{P_b}[\mathrm{kW}] = 3.146 + 0.033x_1 + 0.062x_2 + 0.169x_3 + 4 \times 10^{-4}x_1x_2 + 1.267 \times 10^{-3}x_1x_3 + 9.713 \times 10^{-17}x_2x_3 - 4.344 \times 10^{-3}x_1^2 - 0.031x_2^2 - 0.013x_3^2$
BSFC	$Y_{\mathrm{BSPC}}[g/\mathrm{kWh}] = 421.578 - 18.325x_1 - 12.721x_2 + 5.069x_3 + 1.665x_1x_2 + 0.337x_1x_3 + 1.722x_2x_3 + 1.498x_1^2 + 1.336x_2^2 - 0.989x_3^2$
BTE	$Y_{\mathrm{BTE}}[\%] = 6.879 + 1.621x_1 + 2.163x_2 + 2.537x_3 + 0.094x_1x_2 - 0.042x_1x_3 - 0.157x_2x_3 - 0.067x_1^2 - 0.599 \times 10^{-3}x_2^2 - 0.157x_3^2$
CO	$Y_{\mathrm{CO}}[\%] = -0.447 - 0.058x_1 + 0.565x_2 + 0.327x_3 + 0.010x_1x_2 + 6.666 \times 10^{-3}x_1x_3 - 0.022x_2x_3 + 6.320 \times 10^{-3}x_1^2 - 0.143x_2^2 - 0.026x_3^2$
HC	$Y_{\mathrm{HC}}[\mathrm{ppm}] = 275.544 - 20.380x_1 - 21.722x_2 - 22.238x_3 + 2.266x_1x_2 - 0.466x_1x_3 - 0.444x_2x_3 + 1.952x_1^2 + 7.911x_2^2 + 1.977x_3^2$
CO_2	$Y_{\mathrm{CO_2}}[\%] = 2.752 - 0.152x_1 + 0.319x_2 + 0.120x_3 + 9.333 \times 10^{-3}x_1x_2 - 6.666 \times 10^{-4}x_1x_3 - 0.040x_2x_3 + 0.013x_1^2 - 0.012x_2^2 - 5.333 \times 10^{-3}x_3^2$
NO_x	$Y_{\mathrm{NO}_x}[\mathrm{ppm}] = 36.066 + 14.730x_1 - 2.055x_2 + 19.322x_3 + 0.266x_1x_2 - 0.066x_1x_3 - 0.666x_2x_3 - 1.272x_1^2 - 5.244x_2^2 - 1.422x_3^2$

The quality of the proposed quadratic correlations can be evaluated using analysis of variance which is based on the "F-value" and "P-value." In general, the pattern of interactions between different parameters can be identified considering the F-value and P-value. It should be noted whatever the F-value is larger and the P-value is smaller the corresponding variables are more significant and important. In this regard, a P-value of less than 0.05 demonstrates the substantial factors. Table 11 shows the results of the analysis of variance.

As can be observed in Table 11, in the engine performance section, all of the interaction parameters are not significant (P-value$>$0.05) for torque and brake power. Moreover, the interaction parameters of x_1x_3 and x_2x_3 and the quadratic parameters of x_2^2 and x_3^2 are not significant for BSFC. Besides, the linear term of x_3 is not significant for BTE. Additionally, in the exhaust emission section, all of the interaction terms and the linear terms of x_2 and x_3 are not significant for CO emission. Furthermore, the linear term of x_3 and the interaction term of x_2x_3 are not significant for HC emission. In addition, the linear term of x_3, the interaction terms of x_1x_2 and x_1x_3 and the quadratic terms of x_2^2 and x_3^2 are not significant for CO_2 emission. Finally, all of the interaction terms are not significant for NO_x emission, too. Nonetheless, the F-value of the model for torque, brake power, BSFC, BTE, CO, HC, CO_2 and NO_x emission is 80.85, 67.61, 100.86, 474.75, 39.81, 312.31, 44.72, and 47.69 respectively. Also, the P-value of all models is lower than 0.0001 which implies that all models are highly significant from the statistical point of view. It should be noted that the percentage of water is the most important variable which influences the engine performance and exhaust emission. Furthermore, the "lack of fit P-value" of torque, brake power, BSFC, BTE, CO, HC, CO_2, and NO_x emission model is 0.0511, 0.1929, 0.0672, 0.0659, 0.2089, 0.2410, 0.4469, and 0.0587, respectively which is not significant. The coefficient of determination (R^2) is an indicator that determines the quality of fitting the experimental data with the model. It is preferred that the difference between the predicted coefficient of determination and adjusted coefficient of determination is less than 0.2. The coefficient of variation (CV) is a statistical magnitude of dispersion that characterizes the standard deviation relative to the mean. According to Table 11, the low quantity of the coefficient of variation and the high quantity of coefficient of determination and adjusted coefficient of determination for variables of engine performance and emission emphasize that the regression models can indicate the experimental data with a high level of reliability. The

Table 10 BBDs with corresponding experimental and predicted responses for variables of response

Run	Performance characteristics							
	T/(Nm)		P_b/kW		BSFC/(g·(kWh)$^{-1}$)		BTE/%	
	Exp.	Pre.	Exp.	Pre.	Exp.	Pre.	Exp.	Pre.
1	19.85	19.85	3.78	3.78	391.61	391.80	24.43	24.41
2	19.27	19.23	3.67	3.66	437.80	436.82	25.27	25.23
3	19.56	19.58	3.72	3.73	397.46	398.33	23.76	23.78
4	19.86	19.85	3.79	3.78	386.60	388.47	22.65	22.60
5	19.35	19.36	3.69	3.69	410.99	409.12	24.32	24.36
6	19.89	19.88	3.79	3.79	374.69	371.96	22.60	22.63
7	19.76	19.73	3.76	3.75	371.24	373.00	23.67	23.61
8	19.88	19.85	3.79	3.78	392.84	391.80	24.40	24.41
9	19.15	19.16	3.65	3.65	420.66	423.40	25.00	24.97
10	19.86	19.85	3.78	3.78	389.83	391.80	24.46	24.41
11	19.47	19.50	3.71	3.71	405.54	403.78	24.13	24.19
12	19.65	19.63	3.74	3.74	387.07	386.20	23.33	23.32
13	19.83	19.85	3.77	3.78	391.35	391.80	24.41	24.41
14	19.95	20.00	3.80	3.81	372.28	373.26	22.40	22.44
15	19.30	19.33	3.68	3.68	416.49	416.60	24.57	24.59
16	19.90	19.87	3.78	3.78	383.92	383.81	22.40	22.37
17	19.83	19.85	3.78	3.78	393.38	391.80	24.38	24.41

Run	Emission characteristics							
	CO/%		HC/ppm		CO_2/%		NO_x/ppm	
	Exp.	Pre.	Exp.	Pre.	Exp.	Pre.	Exp.	Pre.
1	0.98	0.99	152	151.60	3.04	3.04	134	134.40
2	1.10	1.08	203	203.37	3.35	3.36	108	106.25
3	0.81	0.81	169	168.25	3.07	3.05	122	124.13
4	0.77	0.79	150	151.37	3.02	3.03	129	127.50
5	1.16	1.14	178	176.63	3.19	3.18	117	118.50
6	0.79	0.78	148	147.37	2.95	2.96	137	136.38
7	0.89	0.88	150	151.00	2.99	2.99	137	135.88
8	1.02	0.99	151	151.60	3.04	3.04	135	134.40
9	1.09	1.11	192	192.63	3.29	3.28	110	110.63
10	0.99	0.99	153	151.60	3.08	3.04	133	134.40
11	0.85	0.86	172	171.00	3.15	3.15	118	119.13
12	0.83	0.83	151	151.75	2.89	2.91	136	133.88
13	0.96	0.99	150	151.60	3.01	3.04	134	134.40
14	0.75	0.77	142	141.62	2.93	2.92	140	141.75
15	1.13	1.16	187	187.38	3.25	3.26	114	113.63
16	0.85	0.83	146	145.62	2.98	2.97	132	132.38
17	0.98	0.99	152	151.60	3.05	3.04	136	134.40

Table 11 ANOVA results and statistical parameters of developed quadratic correlations

Source	Performance characteristics models							
	T/(N·m)		P_b/kW		BSFC/(g·(kWh)$^{-1}$)		BTE/%	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Model	80.85	< 0.0001	67.61	< 0.0001	100.86	< 0.0001	474.75	< 0.0001
x_1	529.63	< 0.0001	434.89	< 0.0001	632.59	< 0.0001	3353.16	< 0.0001
x_2	25.03	0.0016	23.00	0.0020	164.19	< 0.0001	174.44	< 0.0001
x_3	9.57	0.0175	9.22	0.0190	31.03	0.0008	2.58	0.1519
x_1x_2	0.017	0.9013	0.035	0.8572	6.96	0.0336	40.30	0.0004
x_1x_3	4.24	0.0786	1.40	0.2757	1.14	0.3208	32.78	0.0007
x_2x_3	0.066	0.8044	0.000	1.0000	2.68	0.1458	40.63	0.0004
x_1^2	59.61	0.0001	48.06	0.0002	65.85	< 0.0001	239.18	< 0.0001
x_2^2	25.82	0.0014	19.74	0.0030	0.42	0.5357	154.41	< 0.0001
x_3^2	57.59	0.0001	58.29	0.0001	3.72	0.0951	169.86	< 0.0001
Lack of fit	6.50	0.0511	2.56	0.1929	5.47	0.0672	5.53	0.0659
R^2	0.9905		0.9886		0.9923		0.9984	
Adj. R^2	0.9782		0.9740		0.9825		0.9863	
Pred. R^2	0.8710		0.8743		0.8992		0.9784	
Adeq. precision	27.968		25.514		35.719		66.991	
CV[a]/%	0.2		0.21		0.6		0.23	
SD_b	0.039		8.03		2.37		0.056	

Source	Emission characteristics models							
	CO/%		HC/ppm		CO_2/%		NO_x/ppm	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Model	39.81	< 0.0001	312.31	< 0.0001	44.72	< 0.0001	47.69	< 0.0001
x_1	283.91	< 0.0001	1969.63	< 0.0001	274.21	< 0.0001	243.62	< 0.0001
x_2	1.63	0.2425	346.68	< 0.0001	66.29	< 0.0001	86.39	< 0.0001
x_3	0.000	1.0000	3.19	0.1174	0.48	0.5124	6.03	0.0438
x_1x_2	2.09	0.1919	37.60	0.0005	1.87	0.2142	0.25	0.6351
x_1x_3	3.26	0.1140	6.38	0.0395	0.038	0.8508	0.062	0.8112
x_2x_3	3.26	0.1140	0.52	0.4940	12.34	0.0098	0.55	0.4811
x_1^2	8.56	0.0221	326.16	< 0.0001	46.89	0.0002	65.48	< 0.0001
x_2^2	35.57	0.0006	43.39	0.0003	0.31	0.5925	9.02	0.0199
x_3^2	20.09	0.0029	43.39	0.0003	0.92	0.3685	10.61	0.0139
Lack of fit	20.09	0.2089	2.12	0.2410	1.10	0.4469	5.96	0.0587
R^2	0.9808		0.9975		0.9829		0.9840	
Adj. R^2	0.9562		0.9943		0.9609		0.9633	
Pred. R^2	0.7923		0.9741		0.8619		0.7856	
Adeq. precision	18.006		58.083		22.964		22.959	
CV[a]/%	2.95		0.86		0.83		1.58	
SD[b]	0.028		1.39		0.026		2.02	

Notes: [a]–CV = coefficient of variation; [b]–SD = standard deviation.

graphs of the normal probability plot of the residuals, the residuals against the predicted response values, and the actual values against the predicted values for all responses including torque, brake power, BSFC, BTE, CO, HC, CO_2, and NO_x emission are presented in the supplementary materials.

3.3 Interaction between different operating parameters

The response surface plots of interaction between independent parameters (i.e., water percentage, surfactant percentage, and HLB) and different responses (i.e., torque, brake power, BSFC, BTE, CO, HC, CO_2, and NO_x emission) are shown in Figs. 4–11.

3.3.1 Engine torque and brake power

Figures 4 and 5 indicate the interaction between independent parameters and engine torque and brake power, respectively.

As can be observed, an increase in the water percentage of the emulsion fuel at the constant percentage of surfactant and HLB leads to a decrease in the torque and brake power. For instance, an increment in water content

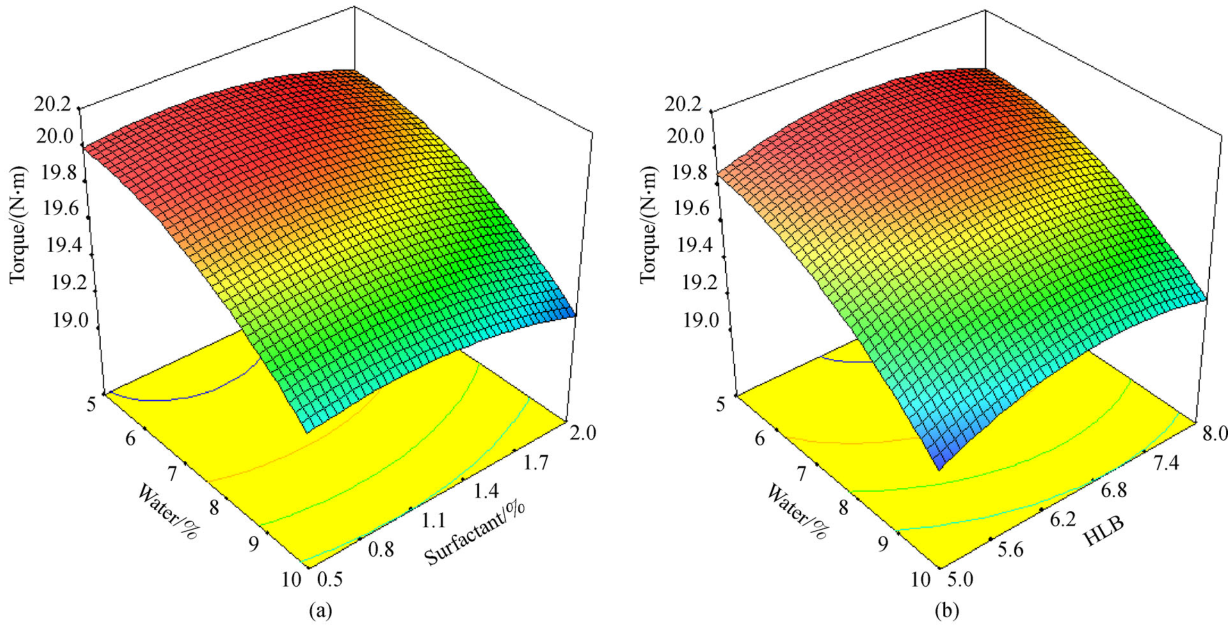


Fig. 4 Response surface plots of torque as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, Full load mode).

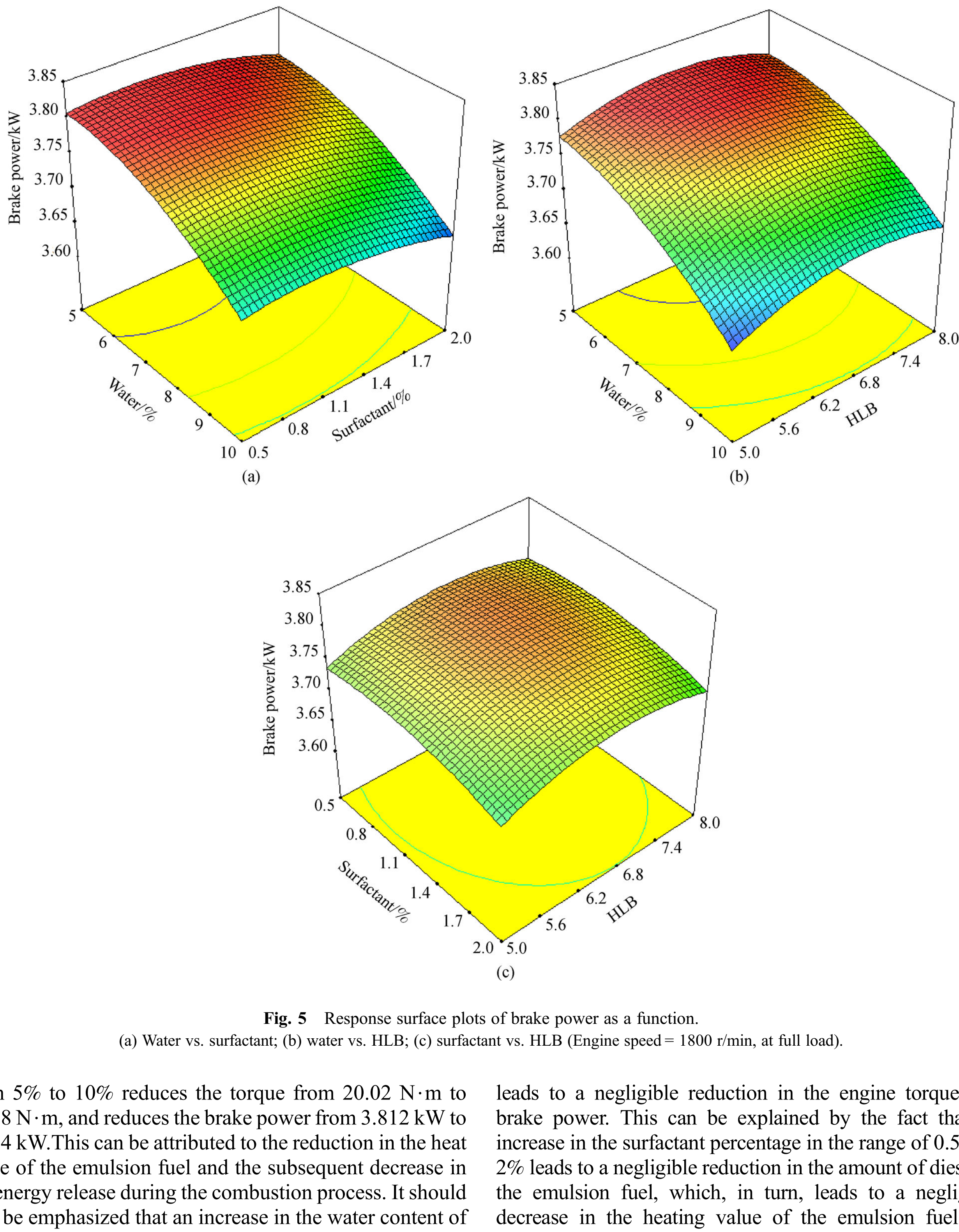


Fig. 5 Response surface plots of brake power as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

from 5% to 10% reduces the torque from 20.02 N·m to 19.38 N·m, and reduces the brake power from 3.812 kW to 3.694 kW.This can be attributed to the reduction in the heat value of the emulsion fuel and the subsequent decrease in the energy release during the combustion process. It should also be emphasized that an increase in the water content of the emulsion fuel leads to an increase in the ignition delay and maximum pressure of cylinder, which, in turn, increases the required compression work and reduces the output energy [4,6].

It can be also observed that increasing the surfactant percentage at the constant water percentage and HLB leads to a negligible reduction in the engine torque and brake power. This can be explained by the fact that an increase in the surfactant percentage in the range of 0.5% to 2% leads to a negligible reduction in the amount of diesel in the emulsion fuel, which, in turn, leads to a negligible decrease in the heating value of the emulsion fuel and subsequent decrease in the torque and brake power. Moreover, the interaction between the percentage of surfactant and HLB is negligible. Ultimately, it can be concluded that the influence of water percentage on the engine torque and brake power is more noticeable in comparison with that of the surfactant percentage and HLB.

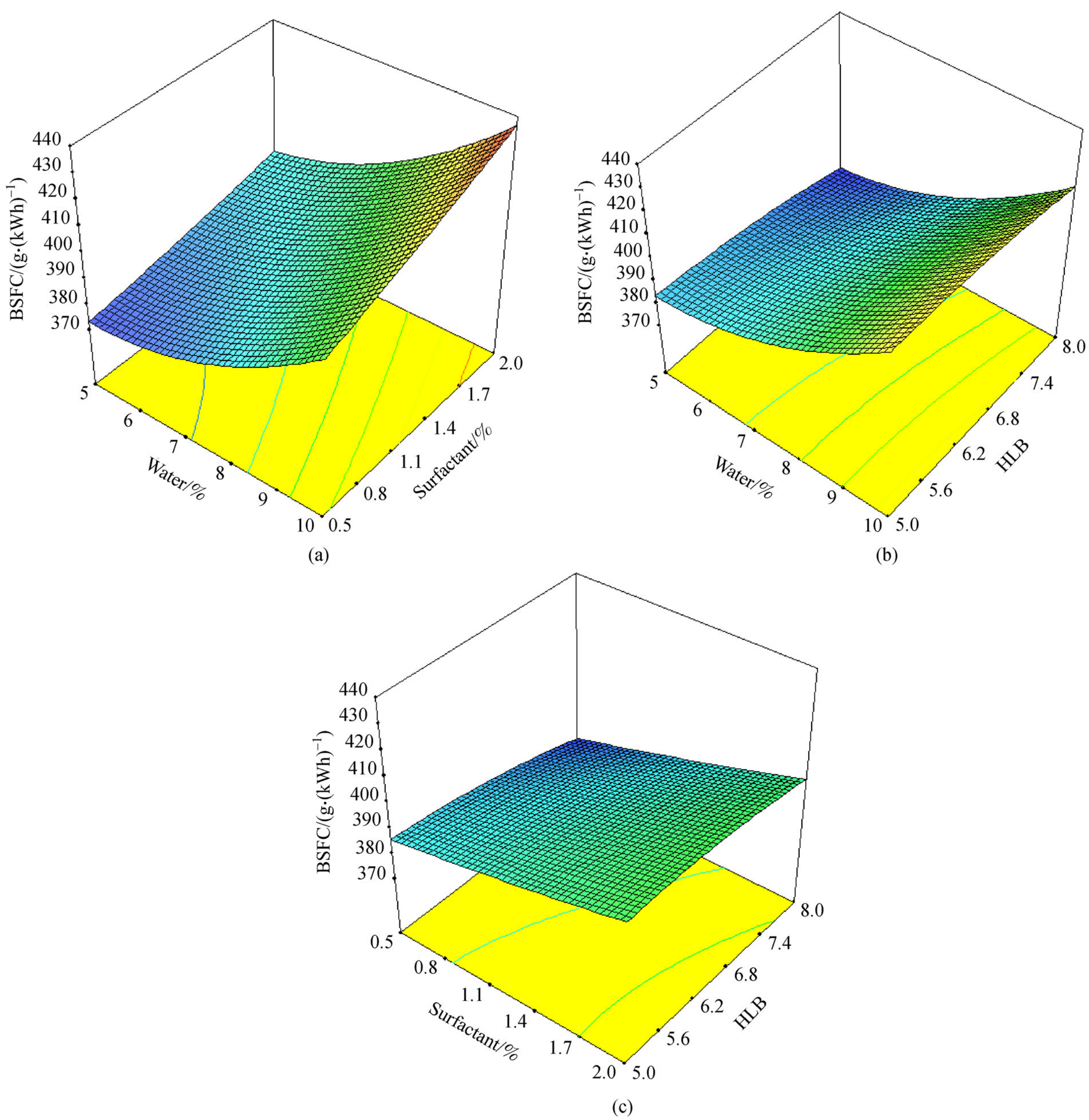


Fig. 6 Response surface plots of BSFC as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

3.3.2 BSFC

Figure 6 demonstrates the interaction between independent parameters (i.e., percentage of water, percentage of surfactant, and HLB) and BSFC as a response variable. As can be observed, an increase in the water percentage at a fixed surfactant percentage and HLB leads to an increment in BSFC. Increasing the water content from 5% to 10% results in a subsequent increase in BSFC from 380.15 g/kWh to 422.12 g/kWh. It should be noted that the presence of water droplets in the emulsion fuel leads to a rapid vaporization of the emulsion fuel and combustion with a longer premixed which in turn results in a more ignition delay and a subsequent more fuel consumption. Besides, the presence of water in the emulsion fuel reduces its calorific value. In this regard, the calorific value is decreased from 41.50 MJ/kg to 33.89 MJ/kg by an increase in the water percentage from 5% to 10%. Moreover, an increase in surfactant contents leads to an increment in BSFC [4,6,10]. This can be attributed to the subsequent reduction of diesel content in the emulsion fuel, which, in turn, increases BFSC. It can be inferred that the impact of water content of the emulsion fuel on the BFSC is more

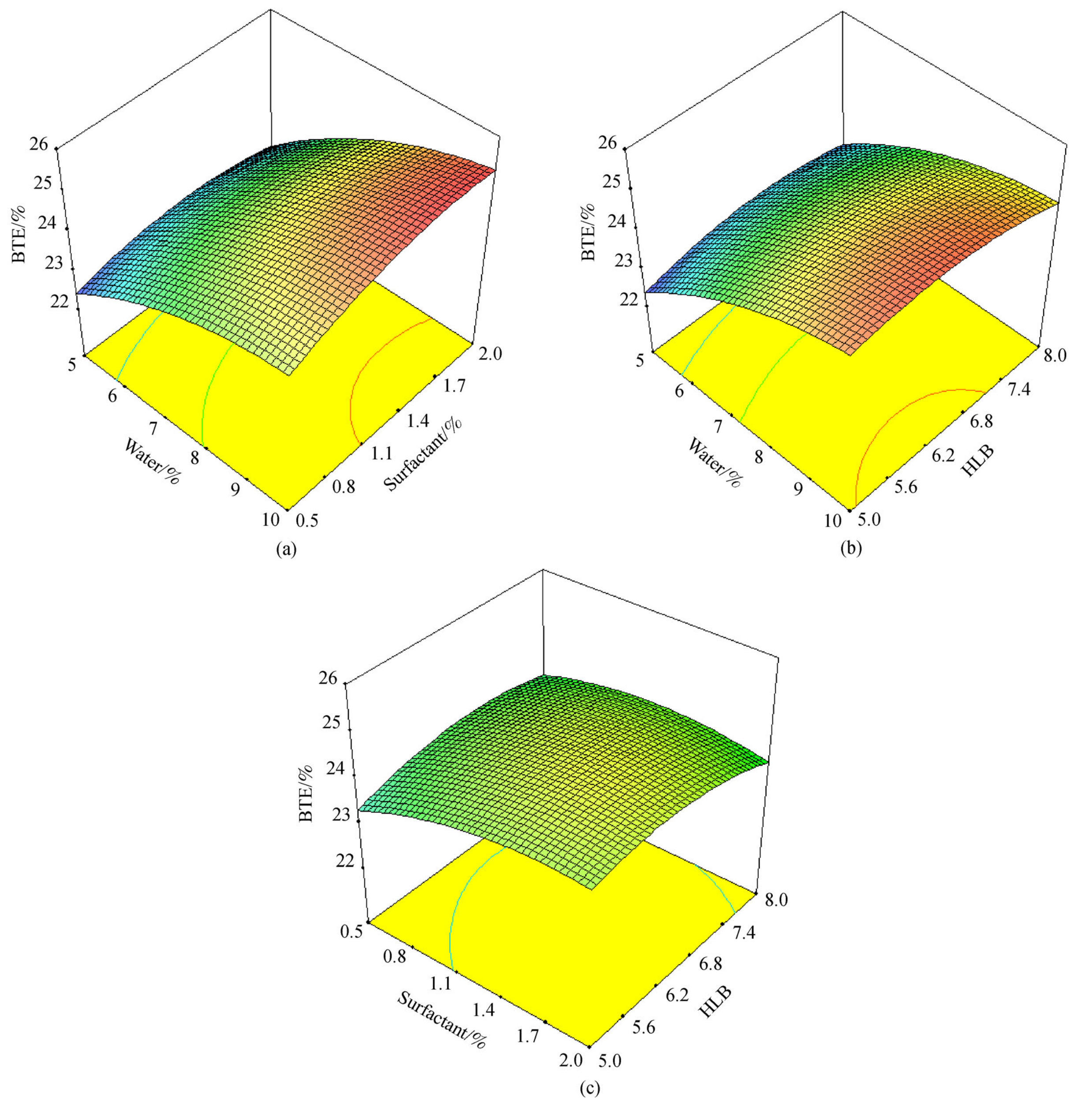


Fig. 7 Response surface plots of BTE as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

pronounced in comparison with other parameters (i.e., surfactant percentage, and HLB).

3.3.3 BTE

Figure 7 indicates the interaction between independent parameters (i.e., percentage of water, percentage of surfactant, and HLB) and BTE as a response variable. As can be observed, an increment in water content from 5% to 10% leads to an increase in the BTE from 22.86% to 25.13%. It should be noted that two factors, i.e., the ignition delay and the micro-explosion phenomena, have remarkable effects on the improvement of thermal efficiency. The increment in ignition delay due to the presence of water leads to an increase in the rate of heat transfer and fuel consumption [4]. It can also be stated that the water addition improves the combustion due to the micro-explosion phenomena. Furthermore, increasing the percentage of water reduces the calorific value of the emulsion fuel, and thus, the thermal efficiency will increase. Therefore, the brake thermal efficiency increases as a result of the increment in water content in the emulsion fuel in constant values of surfactant content and HLB [4,6,10]. It should be noted that the increment in surfactant

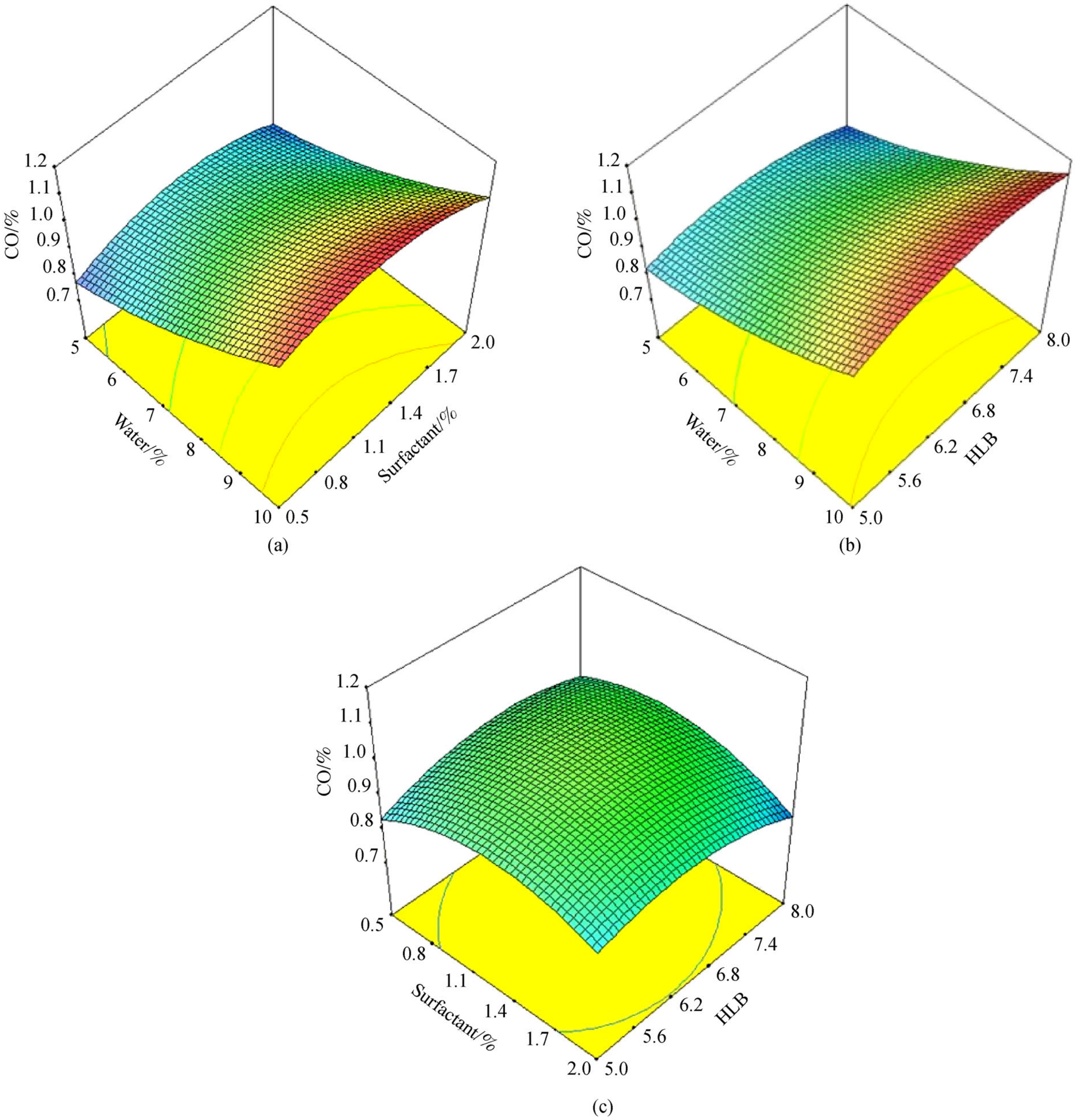


Fig. 8 Response surface plots of CO as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

percentage also increases the thermal efficiency. This is due to the replacement of diesel by an equal amount of surfactant and subsequent decrease in the calorific value. It can be concluded that the impact of water content of the emulsion fuel on the BTE is more noticeable in comparison with other parameters (i.e., surfactant percentage, and HLB).

3.3.4 CO, HC, and CO_2 emissions

The interaction between independent variables (i.e., water percentage, surfactant percentage, and HLB) and response variables of CO, HC, and CO_2 emissions is illustrated in Figs. 8–10, respectively. As can be observed, increasing the water percentage at a constant surfactant percentage and HLB leads to an increment in the carbon oxides and hydrocarbon emission. Increasing the water content from 5% to 10% leads to an increase in the CO emission from 0.86% to 1.18%, the HC emission from 142.3 ppm to 185.51 ppm, and CO_2 emission from 2.98% to 3.28%. It should be noted that the increment in the water content in the emulsion fuels decreases the flame temperature. More-

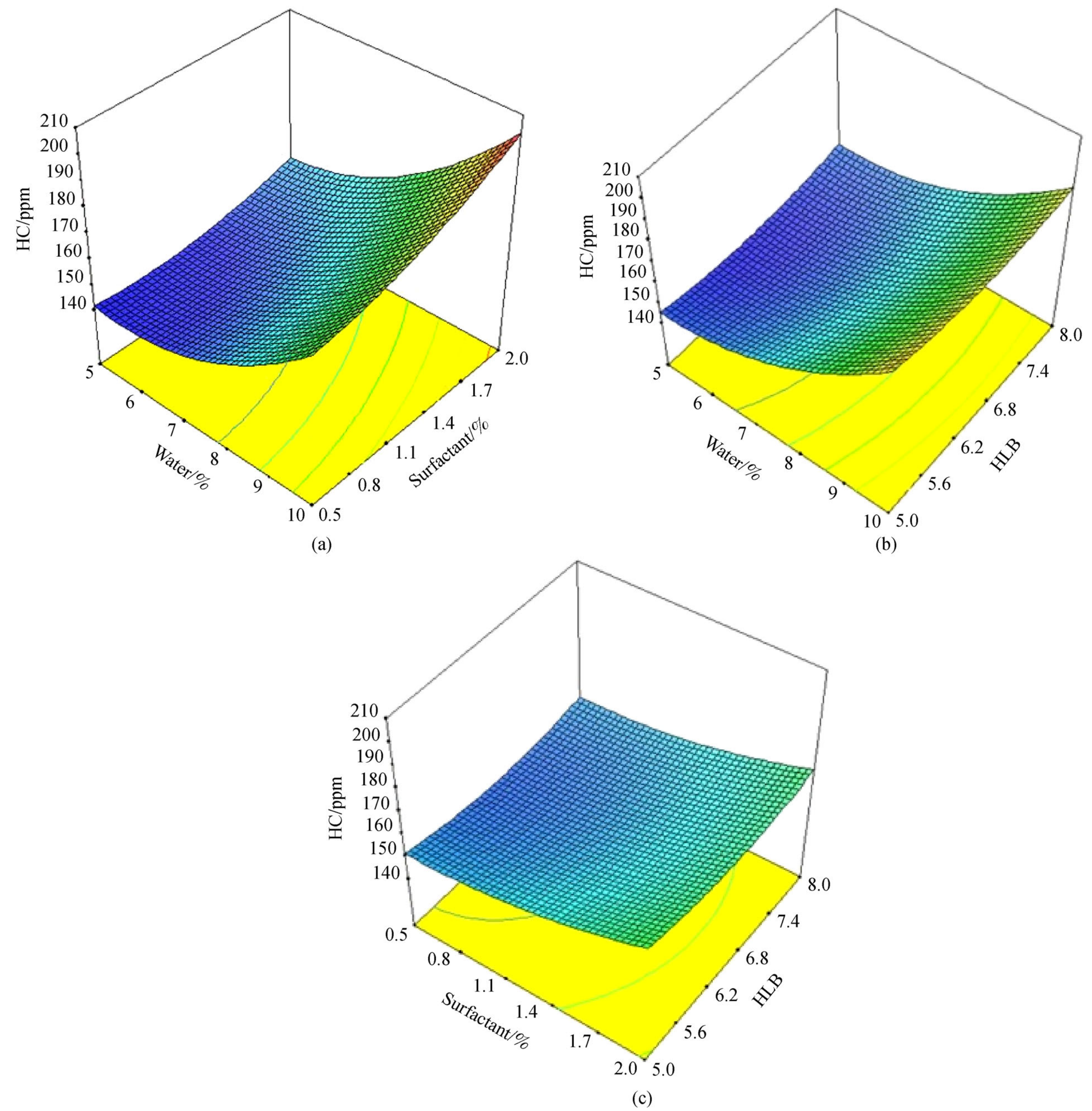


Fig. 9 Response surface plots of HC as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

over, the increment in the water content in the emulsion fuels lowers its calorific value and increases the ignition delay, which, in turn, results in an incomplete combustion and a subsequent increase in CO and HC emission [5,9]. Furthermore, the increment in OH radicals due to the presence of water leads to more oxidation of carbon to carbon monoxide and a subsequent increase in the CO emission [31]. In the case of CO_2 emission, increasing the amount of water in the emulsion fuel leads to an increase in the number of oxygen atoms, which is the main reason for increasing the amount of CO_2 emission of the emulsion fuel compared to the neat diesel fuel [4,31,37]. On the other hand, increasing the surfactant content leads to a slight increment in the emission of carbon oxides and hydrocarbon. As can be observed in Figs. 8–10, the interaction of HLB with the percentage of surfactant and water in the emission of carbon oxides and hydrocarbon is negligible. It can be deduced that the emissions of CO, HC, and CO_2 are mainly influenced by the water content in comparison with the surfactant content and HLB.

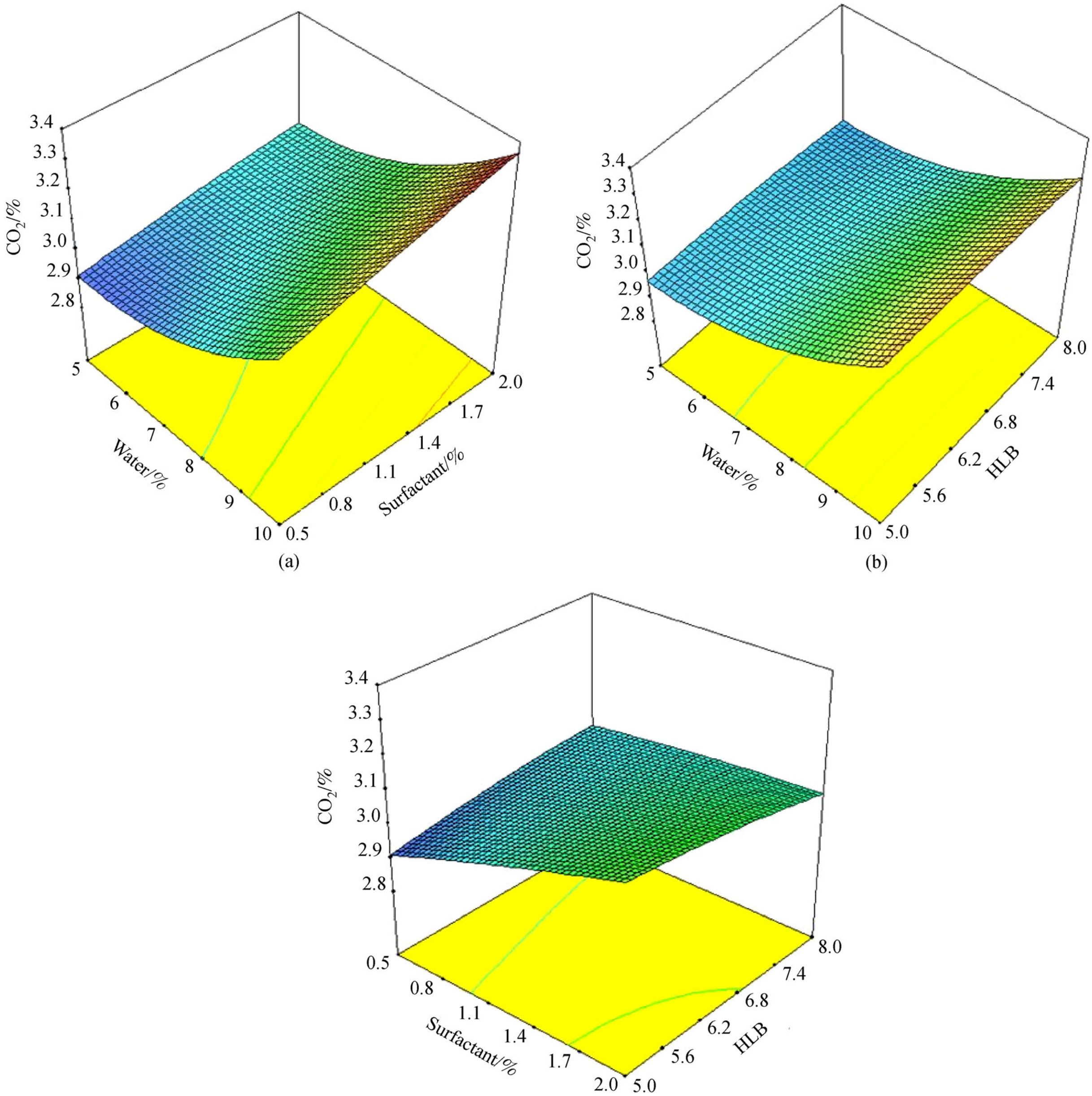


Fig. 10 Response surface plots of CO_2 as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

3.3.5 NO_x emissions

The interaction between independent variables (i.e., water percentage, surfactant percentage, and HLB) and NO_x emission is demonstrated in Fig. 11. As can be observed, the NO_x emission is decreased considerably by increasing the water content at a fixed surfactant percentage and HLB. In this regard, the NO_x emission is reduced from 138 ppm to 116 ppm by an increment in water content from 5% to 10%. It should be noted that the presence of water in the emulsion fuel absorbs part of calorific heat value of the emulsion fuel, which, in turn, leads to a decrement in the temperature inside the combustion enclosure and NO_x emission. In addition, the decrement in NO_x emission for the emulsion fuel can be attributed to the lower peak temperature of the flame achieved in the combustion of the emulsion fuel with a higher water content. On the other perspective, the vaporization of water during the combustion of the emulsion fuel leads to a considerable heat absorption and a subsequent decrement in the temperature. Hence, the decrease in NO_x emission can be attributed to the water-to-steam phase transition, which is called an

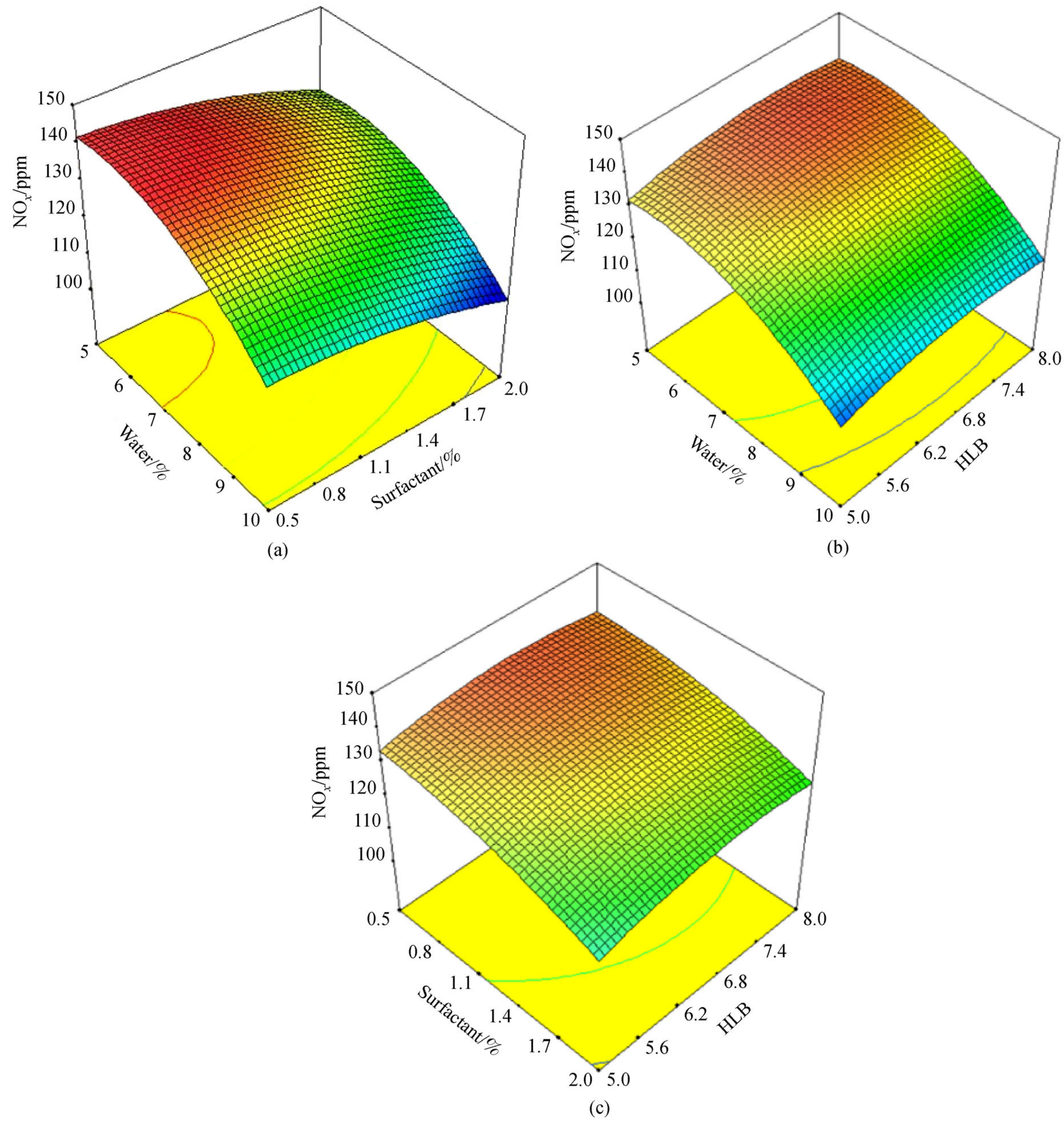


Fig. 11 Response surface plots of NO$_x$ as a function.
(a) Water vs. surfactant; (b) water vs. HLB; (c) surfactant vs. HLB (Engine speed = 1800 r/min, at full load).

endothermic reaction taking place in the combustion enclosure, resulting in the decrement in the cylinder temperature [5,10]. The NO$_x$ emission is decreased to some extent by the increment in the surfactant percentage at a fixed water percentage and HLB. This can be attributed to the subsequent reduction of diesel content in the emulsion fuel, which, in turn, lowers NO$_x$ emission. It should be added that the interaction of HLB with surfactant and water percentage is negligible. As a result, the water percentage plays the major role in the determination of NO$_x$ emission.

3.4 Optimization of engine performance and emission characteristics using RSM

In this paper, one of the major targets is to find the optimum formulation for the water in the diesel emulsion fuel considering three variables (i.e., percentage of water, percentage of surfactant, and HLB) affecting the engine performance and exhaust emission using RSM. The optimization was performed in a multipurpose way. On the one hand, torque, brake power, and brake thermal efficiency should be high and on the other hand, brake specific fuel consumption, and emission of different pollutants such as CO, HC, CO_2 and NO_x should be low. The RSM suggested optimal parameters are summarized in Table 12.

Besides, the predicted responses (i.e., torque, brake power, BTE, BSCF, CO, HC, CO_2, and NO_x emissions) using RSM suggested parameters are compared with the experimental results obtained in three repetitive experiments in Table 12.

As can be observed, the predicted results are in good agreement with the experimental data and the validity of the RSM proposed correlations are confirmed again. In Table 13, the parameters of engine performance using emulsion fuels at RSM suggested appropriate parameters are compared with neat diesel fuel.

3.5 Effect of engine load on engine performance and exhaust emission

In the present paper, the effect of engine load on the performance and emission characteristics was investigated for the best emulsion fuel and the neat diesel fuel at full load and 50% load. The results can be found in Table 14. Regarding to the engine performance parameters, the torque, brake power, and BTE increased by an increase in the engine load for both of the best emulsion fuel and neat diesel fuel. The reason for this is that the frictional losses decrease with the increment in engine load [47]. In addition, the BSFC of the best emulsion fuel and neat diesel fuel decreases by increasing the engine load. It should be mentioned that the improvement in efficiency leads to the reduction of fuel consumption at high load [9,30]. Moreover, the reduction of torque and brake power and the increment in BSFC and BTE of the best emulsion fuel are observed in comparison with the neat diesel fuel at different engine loads. In terms of emission characteristics, the increment in CO, HC, and CO_2 emission and decrement of NO_x emission are observed by an increase in the engine load for both fuels. Furthermore, the CO and CO_2 emission of the best emulsion fuel are increased at full load compared to the neat diesel fuel. HC and NO_x emission are also lower for the best emulsion fuel in comparison with the neat diesel fuel at various engine loads.

Table 12 Validation and repeatability test for engine performance and exhaust emission achieved under optimal conditions

Optimum parameters	Value	Fixed parameters	Value
Water/% (vol)	5	Engine speed	1800 r/min
Surfactant/% (vol)	2	Engine load	100%
HLB	6.8		

Response parameters	Predicted	Experimental Run 1	Experimental Run 2	Experimental Run 3	Average	Error /%
T/(N·m)	19.84	19.86	19.82	19.80	19.83	0.07
P_b/kW	3.781	3.786	3.780	3.788	3.785	0.10
BSFC/(g·(kWh)$^{-1}$)	387.42	386.60	390.06	390.22	388.96	0.40
BTE/%	22.57	22.64	22.44	22.43	22.50	0.30
CO/%	0.77	0.79	0.75	0.81	0.78	1.70
HC/ppm	152.06	150	149	159	153	0.40
CO_2/%	3.02	3.05	2.94	2.97	2.99	1.12
NO_x/ppm	128.63	124	132	133	130	0.80

Table 13 Comparison of engine performance and exhaust emission for the best emulsion fuel and neat diesel fuel at an engine speed of 1800 r/min and full load

Response parameters	Best emulsion fuel	Neat diesel fuel
T/(N·m)	19.83	21.56
P_b/kW	3.785	4.12
BSFC/(g·(kWh)$^{-1}$)	388.96	362.47
BTE/%	22.50	21.39
CO/%	0.78	0.69
HC/ppm	153	166
CO_2/%	2.99	2.85
NO_x/ppm	130	159

Table 14 Effect of engine load on engine performance and exhaust emission

Fuel type/load/%	Engine performance				Exhaust emission			
	T/(N·m)	P_b/kW	BSFC/(g·(kWh)$^{-1}$)	BTE/%	CO/%	HC/ppm	CO_2/%	NO_x/ppm
Best emulsion fuel/100	19.83	3.785	388.96	22.50	0.78	153	2.99	130
Neat diesel fuel/100	21.56	4.120	362.47	21.39	0.69	166	2.85	159
Best emulsion fuel/50	9.76	1.860	511.56	17.11	0.10	63	2.31	154
Neat diesel fuel/50	11.53	2.196	460.48	16.84	0.17	78	2.38	207

4 Conclusions

Water in diesel emulsion fuel is composed of petro-diesel, water, and surfactant. In the present paper, RSM based on BBD was applied to investigate the impact of three parameters including percentage of water, percentage of surfactant, and HLB on the performance and exhaust emission of a single cylinder diesel engine using different emulsion fuels. It was found that the influence of water content on the performance and exhaust variables is more noticeable. Considering multi-objective optimization, the best RSM suggested parameters were 5% for percentage of water, 2% for percentage of surfactant, and 6.8 for HLB. The performance of emulsion fuel produced in the above-mentioned conditions and neat diesel fuel was compared in full load condition at 1800 r/min. It was found that the application of the best emulsion fuel led to a decrease in the torque (–8.02%) and brake power (–8.13%) along with the increment in BSFC (+7.3%) and brake thermal efficiency (BTE) (+5.19%) compared to the neat diesel performance. It was also found that the application of the best emulsion fuel resulted in a considerable decrease in nitrogen oxide (–18.24%) and unburnt hydrocarbon (UHC) (–7.83%) along with the increment in carbon monoxide (CO) (+13.04%) and carbon dioxide (CO_2) (+4.91%) compared to the neat diesel emission.

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