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Optimization the Performance and Emission Parameters of a CI Engine Fueled with Aviation Fuel-Biodiesel-Diesel Blends

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ABSTRACT

The determination of the optimum engine working conditions plays an important role in increasing engine performance and reducing exhaust emissions. The main objective of this study is to optimize the performance and emission characteristics of a CI engine fueled with aviation fuel-biodiesel-diesel blends at various engine speeds and loads using Mixture-RSM. According to the experimental tests carried on a 4-cylinder engine, the mathematical models were developed. Then, the optimization processes were defined as the six scenarios containing the consideration of performance or emission parameters or both of them. Scenario 1 shows that the higher percentage of diesel and jet fuel can improve the performance parameters of the engine; however, Scenario 2 shows that only higher percentage of diesel can improve the engine emission due to negative effect of biodiesel on the NOx emissions and negative impact of aviation fuel on the CO and HC emissions that limit the amount of biodiesel and aviation fuel in the fuel mixture. The results also show that Scenario 3 does not vary compared to Scenario 2. The optimized point for both of engine performance and emission parameters presented in Scenario 6 was calculated as D48.9B32.7J18.4 at 2526 RPM and full engine load to obtain 88.4 (kW), 337 (N.m), 255 (gr/Kw.hr), 0.0268 (%), 469 (ppm), 7.7 (%) brake power, torque, BSFC, CO, NOx, and HC emission, respectively.

1. INTRODUCTION

To analyze engine behavior, linear and non-linear algorithms such as genetic algorithm, artificial neural network, Taguchi method, factorial design, and response surface methodology are used. This algorithm has reduced the number of experimental trials, search time, and expenditure, and it becomes an effective tool for rapid optimization [1].

The optimum working conditions with binary blends based on engine operating parameters by design of experiments (DOE) are established by response surface methodology (RSM) [2,3] provides a high level of information with fewer experiments and data and can transform parameters concurrently throughout optimization [4].

Recently, the optimization of SI engine parameters based on the Taguchi approach was performed by Anand and Karthikeyan [5]. Further, on the performance optimization of diesel particulate filter (DPF) based on adaptive mutative scale chaos optimization algorithm, Zhang et al. [6] found this method very suitable in achieving large filtration efficiency, small pressure drop, low microwave energy consumption, and better emission performance.

In another study [7], the artificial intelligence method was combined with KIVA-3V code to optimize the performance and emission characteristics of a dual-fuel engine. In this research, the operating parameters and chamber shape were optimized, and the regression analysis of the engine parameters was conducted.

Krishnamurthy et al. [8] considered the compression ratio, speed, and load as input factors for diesel engine optimization. This investigation is done through a combination of experimental data analysis and artificial neural network modeling. In this study, the RSM optimization was applied to minimize engine emissions and maximize engine performance. Overall, the results conclude that the application of ANN for prediction and RSM optimization plays an important role in increasing engine performance and reducing exhaust emissions.

Saxena et al. [9] carried out an experimental and statistical analysis on a diesel engine to determine the optimal doping rate of nanoparticles and engine operating parameters applying response surface methodology and desirability function approach. The results showed that the optimal value, TiO_2 doping rate of 150 mg/liter, injection timing of 22.5 °CA bTDC, and 82.37 % engine load would constitute the most suitable combination. This was obtained with an overall high desirability value of 0.707.

In another research [10], the optimization was done for the effect of fuel injection pressure, injection timing, and compression ratio by applying the desirability approach of the RSM. In this paper, the input parameters were taken as 210 bar, 230 bar, and 250 bar for injection pressure, 16, 17, 18 for compression ratios, and 21°, 23°, 25° bTDC for injection timing. The results showed that the maximum BTE of 30.05 % was found at a bar injection pressure of 230 and a compression ratio of 18 with 23° bTDC injection timing. Minimum carbon monoxide of 0.41 % was observed at an injection pressure of 230 bar and a compression ratio of 18 with the injection timing of 25° bTDC, and the oxide of nitrogen of 205.7 ppm was found at an injection pressure of 250 bar and a compression ratio of 16 with 25° bTDC injection timing.

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Singh et al. [11] performed an RSM-based optimization of cassia tora oil blends. In this research, the optimum fuel blends were determined based on diesel engine operating conditions, and biodiesel blends, engine load, injection timing, and injection pressure were as the input parameters. The best combination of the four input parameters was obtained as follows: 15° bTDC fuel injection timing, 221 bar fuel injection pressure, B40 as the fuel blend, and 47 % engine load, resulting in the corresponding output parameters of BTE to be 29.48 % and 43 ppm and 507.60 ppm for HC and NOx emissions, respectively.

In another research [12], the optimized RCCI and DDFS engines fueled with methanol and diesel at low loads were investigated by the multiple-objective optimization. The results showed that the optimization of operating parameters, the fuel properties of methanol, could also be utilized to improve the engine performance, and the co-optimization of operating parameters and fuel properties offers a promising approach to the development of advanced internal combustion engines to meet more stringent requirements on both engine efficiency and engine-out emissions in the future.

Cho et al. [13] performed a multi-objective Pareto optimization to minimize both BSFC and BSNOx. The injection timing and air-fuel ratio were selected as parameters for optimization, and it was possible to improve both variables. The method selects optimum conditions for a given purpose due to the NOx emissions and fuel economy to involve a tradeoff. The results showed that engine-makers could thus minimize fuel consumption when meeting emission criteria.

Niu et al. [14] proposed a novel online optimization approach using NSGA-II coupled with a machine learning method. The optimization approach was conducted based on an engine physical model, which was calibrated and validated carefully using experimental data. The results showed that, based on the Pareto-optimal solutions obtained by the proposed optimization approach, by combining the maps, the solving process of multi-objective optimization problems will be significantly facilitated.

Millo et al. [15] applied random optimization methods and surrogate models to generate a population of engine calibrations, which then served as an initial population to a specifically conceived Genetic Algorithm (GA) based optimizer. It was finally applied to a real data set for a particular engine operating point. The results showed that a large number of optimized calibrations were scattered along with the complete model domain while providing a significant reduction in NOx (20 %) and BSFC (1 %).

Considering that there has not been any research on the use of JP-4 blended with biodiesel in the diesel engines and that this aviation fuel, JP-4, is one of the most important products in Iran by NIOPD Company, this study turned to the optimization of performance and emission characteristics of a CI engine fueled with aviation fuel-biodiesel-diesel blends at different engine speeds and loads using Mixture-RSM.

2. METHODS

2.1. Optimization

One of the important abilities of the Mixture-RSM method is the optimization of complex processes and the evaluation of interactive effects among the variables.

According to the experimental tests based on the matrix obtained from Mixture-RSM, the mathematical models were developed. In this study, the ranges of fuel variables were considered as 0 to 100, 0 to 100, and 0 to 20 for biodiesel, diesel, and Jet Propellant (JP -4) percentage in the fuel mixture, respectively. Moreover, the ranges of 20 to 100 % and 1200 to 2600 RPM were determined for engine loads and speeds, respectively. The specifications of the engine on which experimental tests were carried out are presented in Table 1. In this way, the number of dependent variables was predicted by developed mathematical models.

Table 1. The test engine specifications.

Model	OM364
Number of cylinders	4
Stroke (mm)	133
Bore (mm)	97.5
Compression ratio	17:1
Maximum power	92 kW at 2400 RPM
Maximum torque	455 N.m at 1450 RPM
Cooling system	Water

After that, the optimization of the performance and emission characteristics of the engine was performed according to the results optioned from extracted models.

In the present research, the desirability approach was applied to optimize the independent variables (diesel, biodiesel, and JP-4 percentages in the fuel blend and engine load and speed) for the measured properties of responses (brake power and torque, BSFC, NOx, HC, and CO) [16]. The optimization analysis that was performed by Design Expert version 7 and the responses of brake power and brake torque were selected to be maximized, and HC, CO, NOx, and BSFC were considered to be minimized in the software.

The optimization process in this research is included in six scenarios:

- Scenario 1: Determination of the optimized area considering the performance parameters of the engine (the limits of optimization criteria were defined as the half value of the brake power and torque as the lower limit and the maximum value of these parameters as the upper limit; in addition to BSFC, the limits were defined as the minimum value of this parameter as the lower limit and the half value of it as the upper limit).
- Scenario 2: Determination of the optimized area considering the emission parameters of the engine (the limits of the optimization criteria were defined as the minimum value of the emission parameters as the lower limit and the half value of the emission parameters as the upper limit).
- Scenario 3: Determination of the optimized area considering both performance and emission parameters of the engine (the limits of the optimization criteria were defined as the combination of the lower and upper limits of Scenarios 1 and 2).
- Scenario 4: Determination of the optimized point with the higher importance weight of the performance parameters of the engine (the optimization criteria were defined with an importance weight of 5 for the performance parameters and an importance weight of 3 for emission parameters).
- Scenario 5: Determination of the optimized point with the importance of the emission parameters of the engine (the optimization criteria was defined with an importance

weight of 3 for the performance parameters and an importance weight of 5 for emission parameters).

- Scenario 6: Determination of the optimized point with the importance of the both of performance and emission parameters of the engine (the optimization criteria were defined with an importance weight of 5 for both of performance and emission parameters).

3. RESULTS AND DISCUSSION

3.1. The maximum and minimum value of parameters

According to the extracted models, the maximum and minimum values of the performance and emission parameters are shown in Table 2.

Table 2. The maximum and minimum values of parameters.

Variable	Data	
	Minimum	Maximum
Brake power (Kw)	5.6	95.6
Brake torque (N.m)	41.9	435.5
BSFC (gr/kw.hr)	207	476
CO (%)	0.015	0.062
HC (ppm)	2	25
NO_x (ppm)	138	841

3.2. Optimized area with consideration of performance parameters

The optimized area (red color) with the consideration of performance parameters is presented in Figures 1 and 2.

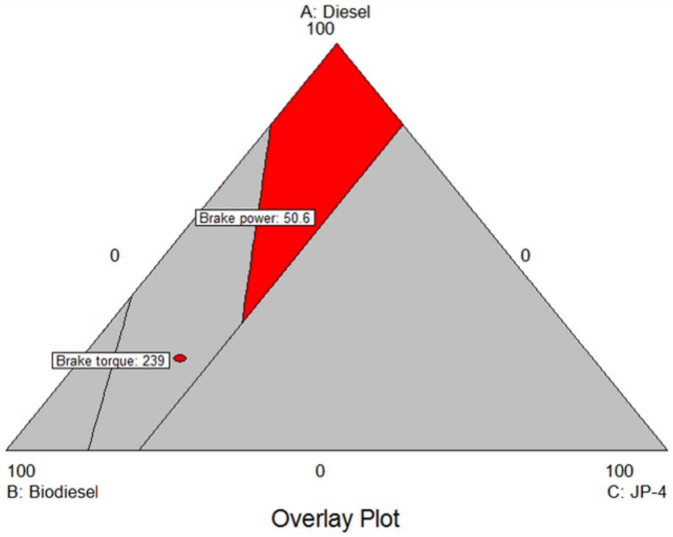

Figure 1. Optimized area with the consideration of performance parameters at a speed of 1900 RPM and an engine load of 60 %.

According to Figure 1, the optimized area at a speed of 1900 RPM and an engine load of 60 % belongs to the fuel blends including 30 to 50 % biodiesel. In addition, in this area, the percentage of diesel and jet fuel changes from 75 to 100 % and 0 to 20 %, respectively. This issue shows that a higher percentage of diesel and jet fuel can improve the performance parameters of the engine.

Based on Figure 2, the optimized area for fuel mixture D50B40J10 belongs to an engine speed of more than 1300 RPM and an engine load of more than 55 %.

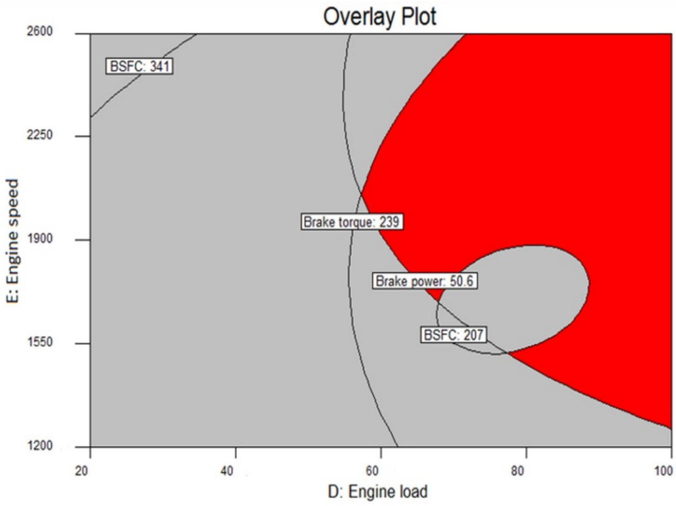

Figure 2. Optimized area with the consideration of engine performance parameters for fuel mixture D50B40J10.

3.3. Optimized area with consideration of emission parameters

The optimized area (red color) with the consideration of emission parameters is presented in Figures 3 and 4.

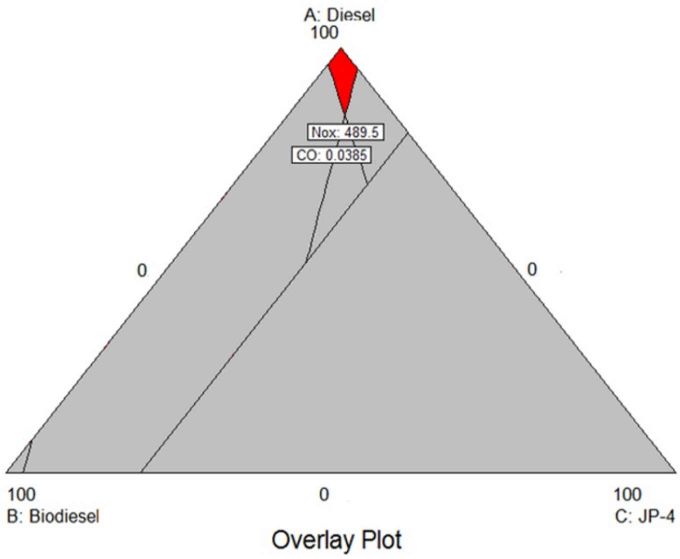

Figure 3. Optimized area with consideration of emission parameters at a speed of 1900 RPM and an engine load of 60 %.

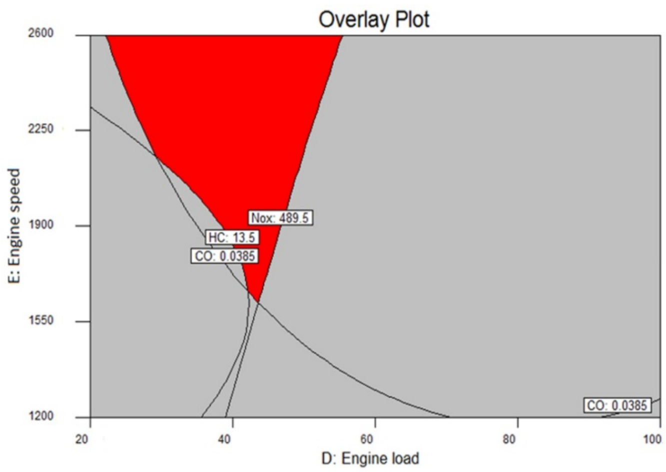

Figure 4. Optimized area with consideration of emission parameters for a fuel mixture of D50B40J10.

According to Figure 3, the optimized area at a speed of 1900 RPM and an engine load of 60 % belongs to the fuel blends including 0 to 10 % biodiesel. In addition, in this area, the percentage of diesel and jet fuel changes from 85 to 100 % and from 0 to 7 %, respectively. This issue shows that only a higher percentage of diesel can improve the engine parameters of the engine. This is due to the important role of biodiesel that has a negative effect on NOx emissions [17-20]. On the other hand, the negative impact of JP-4 on the CO and HC emissions limits the amount of aviation fuel in the fuel mixture [21-26]. Based on Figure 4, the optimized area for fuel mixture D50B40J10 belongs to an engine speed of more than 1600 RPM and an engine load lower than 45 %. This scenario showed that the optimum values of emission parameters overall occurred at lower engine loads in contrast with the optimum values of performance parameters that belonged to higher engine loads.

3.4. Optimized area with the consideration of both performance and emission parameters

The optimized area (red color) with the consideration of performance and emission parameters is presented in Figures 5 and 6.

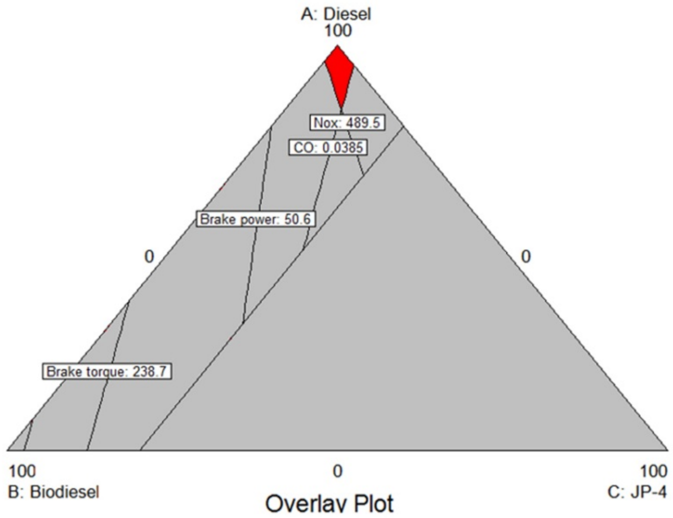

Figure 5. Optimized area with the consideration of both performance and emission parameters at a speed of 1900 RPM and an engine load of 60 %.

According to Figure 5, the optimized area at a speed of 1900 RPM and an engine load of 60 % belongs to the fuel blends including 0 to 10 % biodiesel. In addition, in this area, the percentage of diesel and jet fuel changes from 85 to 100 % and from 0 to 7 %, respectively. This issue shows that this plot did not change compared with the optimization scenario that included the consideration of the emission parameters. This is due to the negative effect of biodiesel on the NOx emission and negative impact of JP-4 on the CO and HC emissions.

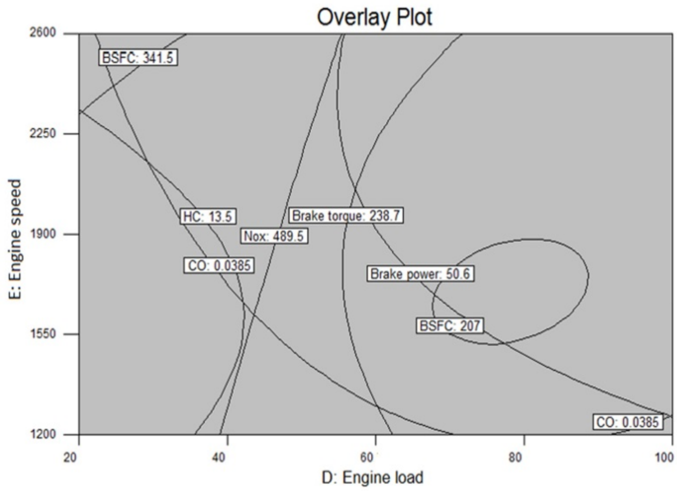

Figure 6. Optimized area with the consideration of both of performance and emission parameters for the fuel mixture of D50B40J10.

Based on Figure 6, there is no overlapped area as the optimized area for the fuel mixture D50B40J10 to satisfy the condition of both performance and emission parameters.

3.5. Optimized point with the higher importance for the performance parameters of the engine

The criteria for the optimization (weights and importance of the parameters, lower and upper limits, and the target of the responses) are presented in Table 3. Different solutions were achieved by the desirability-based approach, and the solution with high desirability was utilized.

The optimized point of the following independent parameters is fuel blend including 100 % diesel at 2344 RPM and full (100 %) engine load by obtaining the maximum desirability of 0.98. In this condition, the optimized values include 89.1 (kW), 371.2 (N.m), 230.9 (gr/Kw.hr), 0.03 (%), 435 (ppm), and 9.4 (%) for brake power, torque, BSFC, CO, NOx, and HC emissions, respectively.

Table 3. The criteria of the optimization.

Variable	Weights		Importance	Criterion
	Lower	Upper		
Diesel percentage in fuel mixture (%)	-	-	-	In-range
Biodiesel percentage in fuel mixture (%)	-	-	-	In-range
JP-4 percentage in fuel mixture (%)	-	-	-	In-range
Engine speed (RPM)	-	-	-	In-range
Engine load (%)	-	-	-	In-range
Brake power (Kw)	0.1	1	5	Minimize
Brake torque (N.m)	0.1	1	5	Minimize
BSFC (gr/kw.hr)	1	0.1	5	Minimize
CO (%)	1	0.1	3	Minimize
HC (ppm)	1	0.1	3	Minimize
NO_x (ppm)	1	0.1	3	Minimize

3.6. Optimized point with the higher importance of the emission parameters of the engine

The criteria for the optimization (weights and importance of the parameters, lower and upper limits, and the target of the responses) are presented in Table 4. Different solutions were achieved by the desirability-based approach, and the solution with high desirability was utilized.

Table 4. The criteria of the optimization.

Variable	Weights		Importance	Criterion
	Lower	Upper		
Diesel percentage in fuel mixture (%)	-	-	-	In-range
Biodiesel percentage in fuel mixture (%)	-	-	-	In-range
JP-4 percentage in fuel mixture (%)	-	-	-	In-range
Engine speed (RPM)	-	-	-	In-range
Engine load (%)	-	-	-	In-range
Brake power (Kw)	0.1	1	3	Minimize
Brake torque (N.m)	0.1	1	3	Minimize
BSFC (gr/kw.hr)	1	0.1	3	Minimize
CO (%)	1	0.1	5	Minimize
HC (ppm)	1	0.1	5	Minimize
NO_x (ppm)	1	0.1	5	Minimize

The optimized point for the following independent parameters was fuel blend including 31 % diesel, 50.7 % biodiesel, 18.3 % JP-4 at 2600 RPM and full engine load by obtaining the maximum desirability of 0.968. In this condition, the optimized values include 87 (kW), 320 (N.m), 268 (gr/Kw.hr), 0.0236 (%), 505 (ppm), and 5.9 (%) for brake power, torque, BSFC, CO, NOx, and HC emissions, respectively.

3.7. Optimized point with the same importance of the performance and emission parameters of the engine

The criteria for the optimization (weights and importance of the parameters, lower and upper limits, and the target of the responses) are presented in Table 5. Different solutions were achieved by the desirability-based approach, and the solution with high desirability was utilized.

Table 5. The criteria of the optimization.

Variable	Weights		Importance	Criterion
	Lower	Upper		
Diesel percentage in fuel mixture (%)	-	-	-	In-range
Biodiesel percentage in fuel mixture (%)	-	-	-	In-range
JP-4 percentage in fuel mixture (%)	-	-	-	In-range
Engine speed (RPM)	-	-	-	In-range
Engine load (%)	-	-	-	In-range
Brake power (Kw)	0.1	1	3	Minimize
Brake torque (N.m)	0.1	1	3	Minimize
BSFC (gr/kw.hr)	1	0.1	3	Minimize
CO (%)	1	0.1	3	Minimize
HC (ppm)	1	0.1	3	Minimize
NO_x (ppm)	1	0.1	3	Minimize

The optimized point of the following independent parameters was fuel blend including 48.9 % diesel, 32.7 % biodiesel, and 18.4 % JP-4 at 2526 RPM and full engine load by obtaining the maximum desirability of 0.97. In this condition, the optimized values are 88.4 (kW), 337 (N.m), 255 (gr/Kw.hr), 0.0268 (%), 469 (ppm), and 7.7 (%) for brake power, torque, BSFC, CO, NOx, and HC emissions, respectively.

4. CONCLUSIONS

The main objective of this study was the optimization of the performance and emission characteristics of a CI engine fueled with aviation fuel-biodiesel-diesel blends at different engine speeds and loads using Mixture-RSM. According to the results, it was concluded that:

a) The optimized area in Scenario 1 showed that a higher percentage of diesel and jet fuel could improve the performance parameters of the engine.
b) The optimized area in Scenario 1 for fuel mixture D50B40J10 showed that the higher performance of the engine occurred at higher engine speeds and loads.
c) The optimized area in Scenario 2 showed that only a higher percentage of diesel could improve the engine parameters of the engine. This is due to the negative effect of biodiesel on the NOx emissions and negative impact of JP-4 on the CO and HC emissions limiting the amount of biodiesel and aviation fuel in the fuel mixture.
d) The optimized area in Scenario 2 for fuel mixture D50B40J10 showed that the better emission values of the engine occurred at higher engine speeds and lower engine loads.
e) The optimized area in Scenario 3 did not change compared with Scenario 2 due to the negative effect of biodiesel on the NOx emission and negative impact of JP-4 on the CO and HC emissions.
f) There was no overlapped area as the optimized area for the fuel mixture D50B40J10 to satisfy the condition of both performance and emission parameters.
g) In Scenario 4, the optimized point was D100 at an engine speed of 2344 RPM and full engine load to obtain 89.1 (kW), 371.2 (N.m), 230.9 (gr/Kw.hr), 0.03 (%), 435 (ppm), and 9.4 (%) for brake power, torque, BSFC, CO, NOx, and HC emission, respectively.
h) In Scenario 5, the optimized point was D31B50.7J18.3 at 2600 RPM and full engine load to obtain 87 (kW), 320 (N.m), 268 (gr/Kw.hr), 0.0236 (%), 505 (ppm), and 5.9 (%) for the brake power, torque, BSFC, CO, NOx, and HC emissions, respectively.
i) In Scenario 6, the optimized point was D48.9B32.7J18.4 at 2526 RPM and full engine load to obtain 88.4 (kW), 337 (N.m), 255 (gr/Kw.hr), 0.0268 (%), 469 (ppm), and 7.7 (%) for brake power, torque, BSFC, CO, NOx, and HC emission, respectively.

It is recommended that other optimization methods be used and compared with Mixture-RSM method. Moreover, the fuel mixture included diesel-biodiesel-alcohol-aviation that could be evaluated and optimized for the diesel engine.

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