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Optimization of Engine Performance and Emissions Using Ethanol-Fusel Oil Blends: A Response Surface Methodology

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Abstract
This study evaluates the performance of a turbocharged spark ignition (SI) engine using a mixture of ethanol and fusel oil with gasoline (RON95) to assess engine performance, emissions, and combustion stability. This study utilizes Response Surface Methodology (RSM) to optimize the influence of engine speed, engine throttle, and fuel mixture on engine performance parameters, thermal efficiency, specific fuel consumption, and exhaust emissions. The experimental results show that COVimep (coefficient of variation of mean pressure in the cylinder) increases with adding ethanol and fusel oil proportions, with F30 showing the highest COVimep (2.80%). Optimization using RSM shows optimal conditions at an engine speed of 3000 rpm, 40% throttle, and F30 mixture, resulting in 33.0 kW of brake power, 35% thermal efficiency, 285.4 g/kWh of specific fuel consumption, and NOx, HC, and CO emissions of 1013.7 ppm, 185.3 ppm, and 1.59%, respectively. Validation experiments with the same conditions showed a brake power of 34.5 kW, thermal efficiency of 36%, and slightly increased emissions. The optimization results showed that RSM effectively optimises engine performance and emissions with a prediction error of less than 5% and can be applied to various fuel mixture combinations.

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1. Introduction
Using alternative fuels in internal combustion engines (ICEs) has become a significant topic to reduce dependence on fossil fuels and reduce the environmental impact of vehicle emissions. One promising alternative fuel is ethanol blends, which can reduce carbon dioxide (CO_2) emissions and improve engine performance when used in the proper proportions. Previous studies have shown that adding ethanol to

gasoline can increase octane, which increases combustion efficiency [1–3]. However, this blend can also affect engine operating stability, especially regarding in-cylinder pressure fluctuations as measured by the coefficient of variation of mean in-cylinder pressure (COVimep) [4–7]. The effect of ethanol on engine operating stability is often associated with increased flame speed and higher cyclic pressure, potentially reducing engine stability.

In addition to ethanol, fusel oil, a by-product of alcohol fermentation, has also been identified as a potential fuel for internal combustion engines [8–10]. Blends of gasoline with fusel oil provide different combustion characteristics, especially regarding flame speed and combustion stability. The fusel oil has a higher water content, affecting the evaporation rate and fuel-air mixture formation, thus affecting engine performance [11–14]. Adding fusel oil to the fuel mixture can also increase the octane value, potentially improving engine efficiency and affecting combustion stability and exhaust emissions. Previous studies have discussed various approaches to evaluate the impact of alternative fuel blends on engine performance and emissions, one of which is using statistical analysis methods such as Response Surface Methodology (RSM). RSM has been used to optimize the influence of parameters such as engine speed, engine throttle, and fuel blend on engine performance parameters such as brake power, thermal efficiency, and brake-specific fuel consumption [15–18]. By using RSM, factors that affect emissions, such as nitrogen oxides (NOx), hydrocarbons (HC), and carbon monoxide (CO), can be analyzed more comprehensively, allowing the identification of optimal engine operating conditions.

Studies on the effect of ethanol and fusel oil mixtures on exhaust emissions have shown that this fuel mixture can produce lower NOx and HC emissions but with a more complex impact on CO [19–23]. Although ethanol can reduce CO emissions, fusel oil can potentially increase CO emissions due to its composition, which is richer in carbon compounds [24–29]. This study aims to evaluate engine performance, fuel efficiency, and exhaust emissions of a turbocharged SI engine using various ethanol and fusel oil mixtures, focusing on the effect of the mixture ratio on combustion stability and engine performance. One of the crucial parameters in evaluating combustion stability is COVimep, which measures the cyclic variation in cylinder pressure. Research by Sen et al. [30] revealed that an increase in COVimep can decrease combustion stability, leading to discomfort for passengers, especially in engines using a mixture of alcohol fuels with gasoline. Therefore, it is crucial to understand how fuel mixtures such as ethanol and fusel oil affect COVimep and its relationship to engine operating stability and occupant comfort.

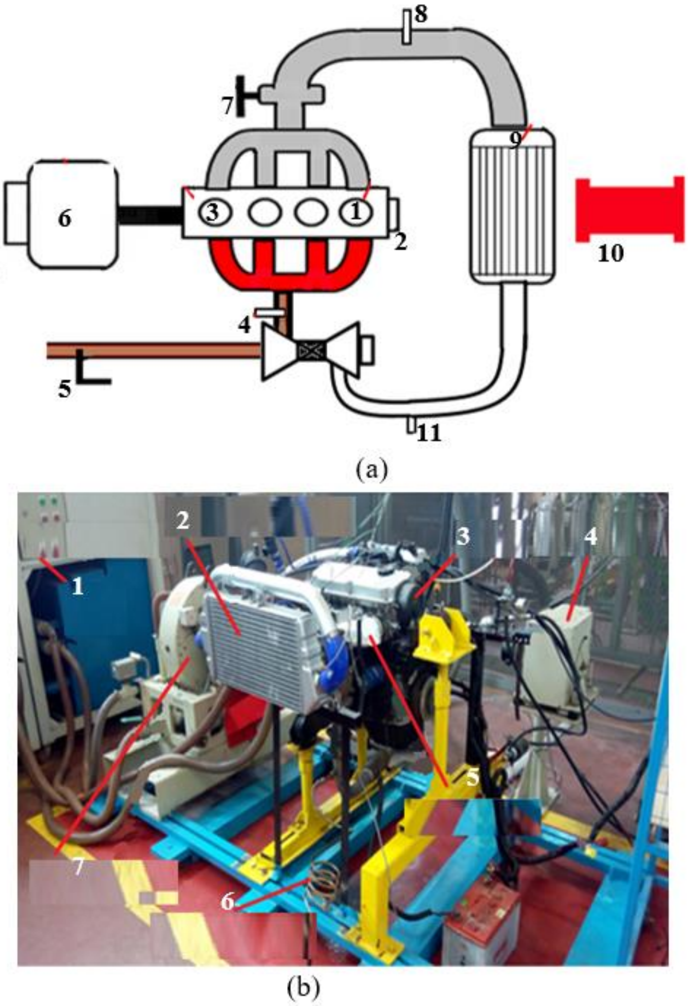
This study investigates the impact of ethanol and fusel oil mixtures on engine performance, fuel efficiency, emissions, and combustion stability. Using RSM, this study optimizes the influence of factors such as engine speed, engine throttle, and fuel mixture ratio on engine performance and emissions [31–34]. Through this approach, this study will provide deeper insight into the potential use of alternative fuel mixtures in internal combustion engines and their contribution to reducing emissions and increasing engine efficiency. In addition, this study also explores how optimizing engine operating conditions can improve braking power and thermal efficiency, reduce specific fuel consumption, and reduce NOx, HC, and CO emissions. This study's results are expected to significantly contribute to developing more environmentally friendly and efficient engine technology and pave the way for using alcohol-based fuel mixtures in motor vehicle applications.

The specific objectives of this study are to analyze the impact of the use of ethanol and fusel oil mixtures on engine performance, fuel efficiency, and exhaust emissions in a turbocharged internal combustion (SI) engine and to optimize engine operating conditions using Response Surface Methodology (RSM). This study aims to understand the effect of fuel mixtures on combustion stability as measured by COVimep and to evaluate the impact of fuel mixture ratios on braking power, thermal efficiency, specific fuel consumption, and NOx, HC, and CO emissions. The novelty of this study lies in the application of fusel oil mixtures as alternative fuels that have not been widely explored in previous studies, as well as the use of RSM to optimize engine operating conditions more comprehensively. In addition, this study provides new insights into the effect of alcohol-based fuel mixture proportions on combustion stability and emissions, which can be a reference for developing more efficient and environmentally friendly engine technology with an approach based on experimental data and in-depth statistical analysis.

2. Methodology

Before the engine started, a data logger device controlled by a personal computer and dynamometer was installed. This was done to capture the data. Several instruments and sensors were installed throughout the engine. The instrumentation consists of a variety of components, some of which are as follows: in-cylinder pressure, thermocouples, air velocity, fuel consumption system, engine dynamometer through coupling connection, and gas analysis prop. Considering this, the electronic control unit (ECU), the engine installation equipment, and the turbocharger system have all been finished. A description of the experimental setup and the central facilities that are utilized in engine test beds may be found in this section. Several experimental setups were carried out on the engine test rig, including installing TFX in-cylinder pressure, fuel flow system, emission analyser, and the rewiring of the Haltech electronic control unit and the blueprint for the engine. The primary instruments used to gather information on the engine are the in-cylinder pressure, fuel flow, air intake flow, engine speed, engine torque, and temperature. Detailed information regarding the power and torque curves of the engine may be found in **Table 1**. At the same time, the engine configuration of the test rig in the laboratory is depicted in **Fig. 1(a)** schematic of the engine test rig and **(b)** engine test rig in the laboratory. Both the apparatus and the methodologies utilized in this investigation originated from the engine performance laboratory located inside the Faculty of Mechanical Engineering at Universiti Malaysia Pahang.

1. In-cylinder pressure. 2. Encoder. 3. Engine.
4. Thermocouple. 5. Exhaust gas analyser.
6. Dynamometer. 7. Throttle. 8. Thermocouple
9. Intercooler. 10. Electric fan. 11. Thermocouple.



1. Cooling system. 2. Intercooler. 3. Engine.
4. Throttle control. 5. Turbocharger.
6. Gas analyser prop. 7. Dynamometer.

Fig. 1. (a) Schematic of the engine test rig and (b) Engine test rig in the laboratory

The gasoline engine used throughout this study uses a port injection method to spray the fuels in the port before inter-combustion chambers. **Fig. 2(a)** shows the port injection system integrated with the instrument and measurement of devices. The fuel system consists of two stainless steel tanks (1-meter high from the engine, which contains 20 litres in each tank) to ensure proper safety and pressure. These tanks store fuel during engine testing with one for gasoline and another for fuel blends. All the tanks are appropriately labelled according to their contents. Stainless steel tubing (6mm diameter) delivers fuel from the fuel tanks to the engine fuel injection system. The 12-volt fuel pump pumps the fuel into the injection system. **Fig. 2(b)** shows the fuel pump for the engine. The fuel regulator shown in **Fig. 2(c)** stabilises the fluctuating pressure inline up to 0.35 MPa, which is suitable for the Multipoint Injection (MPI) system. The fuel flow rate is measured with a high-precision fuel flow meter (Model AIC-3033) as **Fig. 2(d)** (the fuel flow sensor).

Table 1. Specification Engine 4G93 SOHC

Item	Detail
Type	SOHC 16 V MPI
Number of cylinders	4
Combustion of Chambers	Pentroof Type
Total displacement	1834 cc
Cylinder bore	81 (mm)
Piston stroke	89 (mm)
Compression ratio	9.5:1
Maximum output	152kW@5500 rpm
Maximum torque	270Nm @3500 rpm
Cooling system	Water cooler
Lubricant system	Sump oil pressure
Fuel system	MPI
Rod Length	133.5 (mm)
Intake valve	Open 20 BTDC - Close 60 ABDC
Exhaust valve	Open 61 BBDC - Close 21 ATDC
Camshaft height	Intake 36mm - Exhaust 35mm
Water pump type	Centrifugal impeller
Oil pump type	Trochoid

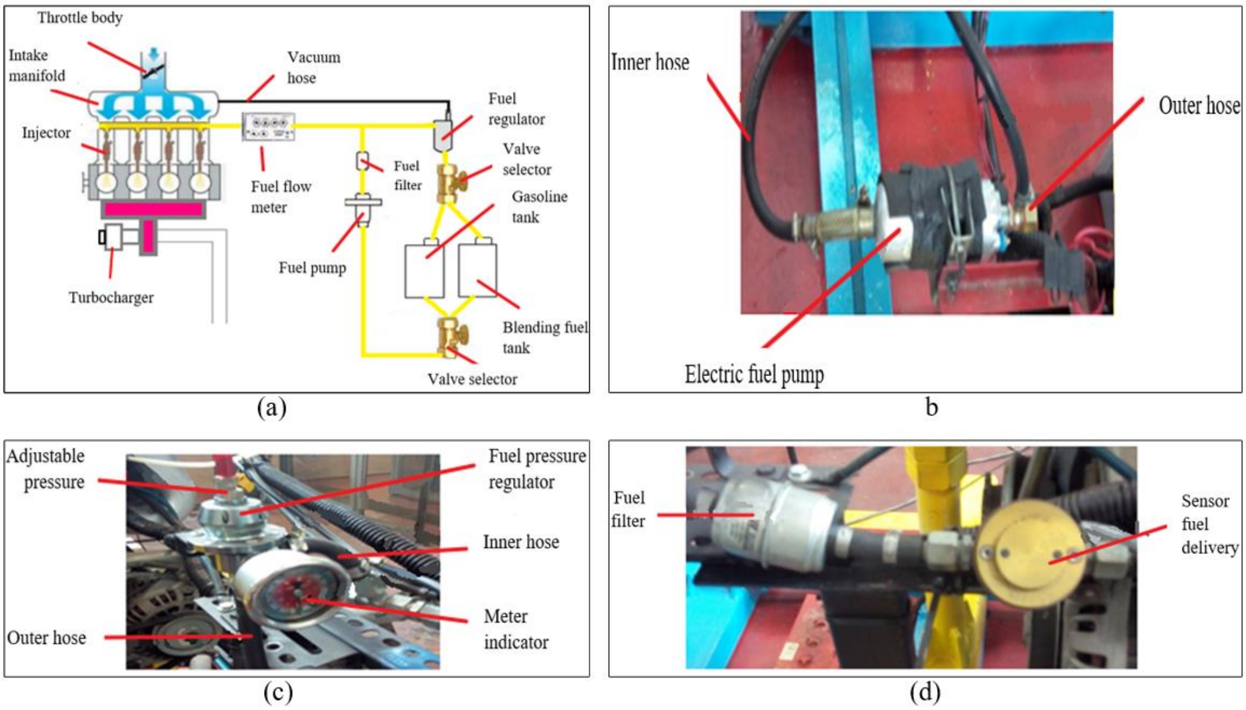


Fig. 2 (a) Schematic diagram of port injection fuel line, (b) Electric fuel pump (12Volt), (c) Fuel regulator for control pressure fuel, and (d) Sensor fuel flow meter assembly

Several methods can be used to optimize experimental data. Response surface methodology (RSM) is widely used to interpret the engine analysis data. It is one of the most influential variables that leads to input response. The results obtained by RSM analyses will provide the best system performance for optimized data sets. The main advantage of this method is that fewer tests are required, and it is less time-consuming compared to accurate data experimental studies. This approach is widely used and has been applied in most automotive sectors. The main idea of implementing RSM is to use a sequence of designed experiments to obtain an optimal response. RSM yields the maximum amount of information from the minimum work. Since all the experiments can be run simultaneously, the result could be obtained quickly.

The significant progress in methodology research has appropriately been discussed in this chapter. All the methods, from fuel blends and fuel properties measurement engine setup, and dynamometer setup, were revealed. Therefore, all instrumentations, software for cylinder pressure, and thermocouple setup were calibrated to ensure the feasibility of achieving standard research. The result for in-cylinder pressure will collected to analyse the COVimep and COVpmax. Then, all data will be compiled into the RSM for optimization.

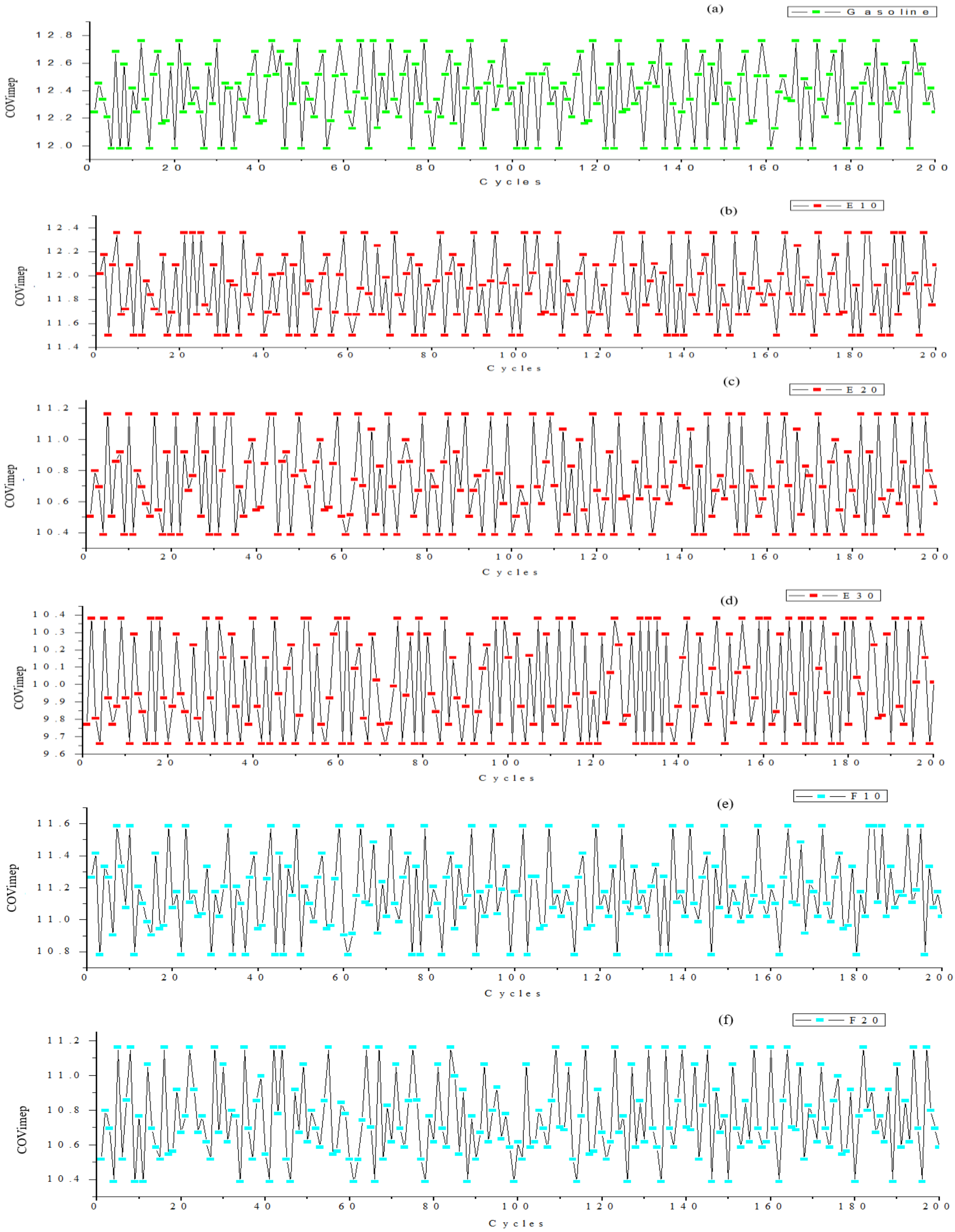
3. Results and Discussions

The COVimep is another significant parameter used to measure the stability of the engine's operation [35]. It shows the cycle-to-cycle variation at ideal calculation. It is adapted to compare the fluctuations of variation between two-time series even when their mean values are pretty different [36]. Indicated mean adequate pressure is the most significant parameter to show the engine output, which is related to in-cylinder pressure traces and is therefore influenced by various factors like the rate of heat release from diluted fuel in the cylinder during the cycle [37]. Wang et al. (2010) described that when COVimep exceeds 10%, the engine operation becomes unstable, and passengers would feel highly uncomfortable. As the proportion of ethanol and fusel oil blends in gasoline increased, it induced lean, higher lamina flame speed and complete combustion. Heywood (1988) mentioned that while the engine is applying a lean air-fuel ratio, the magnitude of COV significantly increases the effect on engine stability. As a result, the COVimep of the engine rises sharply due to higher flame speed at the start of combustion.

Fig. 3 shows COVimep for gasoline fuels, ethanol blends, fusel oil blends at 3000 rpm, and 40% engine throttle. The COVimep for F10, F20, F30, E10, E20 and E30 increased at 6%, 7.7%, 13.9%, 17.5%, 19.7% and 30.5%, respectively, compared to gasoline. The increase in COVimep is due to higher water content, vaporization, and octane in alcohol fuel. **Fig. 4** shows the bar chart for cycle numbers as a function of IMEP for (a) gasoline (G), (b) ethanol blend 10% (E10), (c) ethanol blend 20% (E20), (d) ethanol blend 30% (E30), (e) fusel oil blend 10% (F10), (f) fusel oil blend 20% (F20) and (g) fusel oil blend 30% (F30) using engine speed at 3000 rpm and 40% engine throttle. It revealed that when the proportion of blends increased, the peaks of IMEP reduced dramatically. The reduction of IMEP is due to the decrease of in-cylinder pressure and slight scatter. **Table 2** shows the summary of COVimep using seven fuels in this study. The COVimep E30 is higher than all fuels, while gasoline is lower. The coefficient of variation is 2.03% for gasoline, which is lower than the test for all fuels. It shows that using gasoline is better compared to other fuels. **Fig. 5** shows a summary using a bar chart of maximum COVimep as a function of fuel type. It shows that gasoline has the best COVimep compared to other fuels.

Table 2. The summary of COVimep for all fuels

Parameter	Gasoline	F10	F20	F30	E10	E20	E30
Max pressure (bar)	12.76	11.6	11.1	10.04	12.35	11.2	10.38
Min pressure (bar)	11.97	10.4	10.3	9.34	11.5	10.4	9.65
Average pressure (bar)	12.4	11.2	10.7	9.6	11.9	10.7	9.9
Standard deviation (σ)	0.25	0.24	0.23	0.22	0.29	0.27	0.28
Coefficient of variation (%)	2.03	2.16	2.20	2.36	2.46	2.5	2.8


(a)
Gasoline
COVimep
Cycles
(b)
E10
COVimep
Cycles
(c)
E20
COVimep
Cycles
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COVimep
Cycles

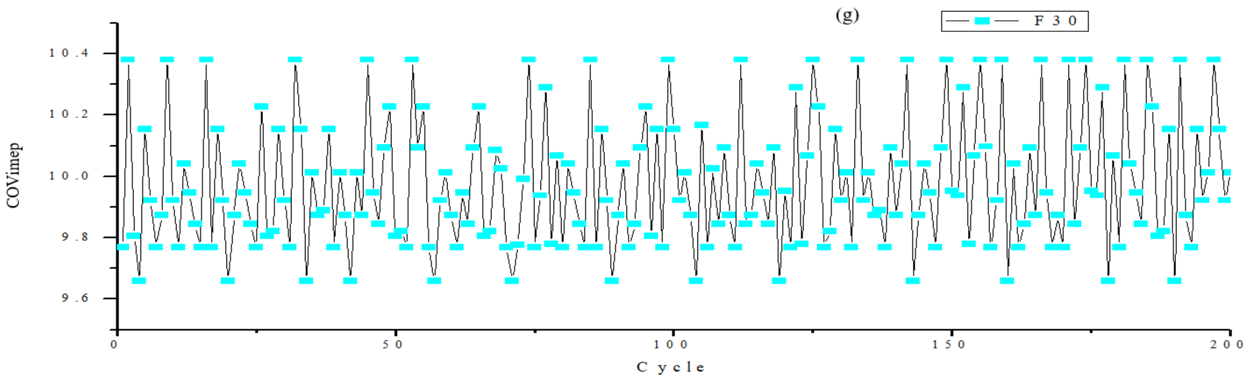

Fig. 3. COVimep at 3000 rpm and 40% engine throttle for 200 cycles

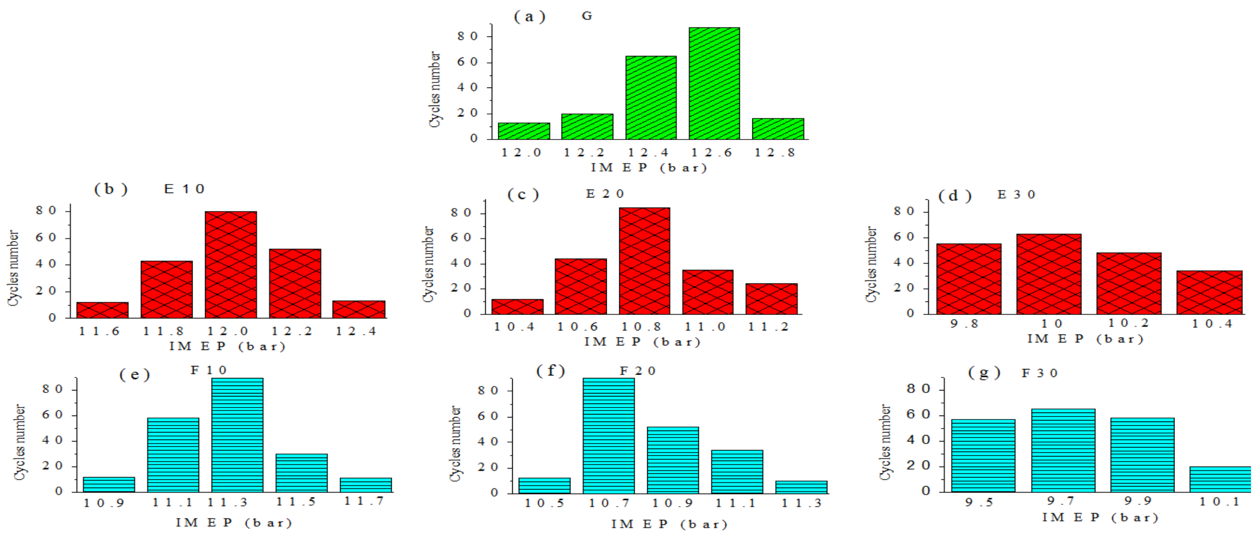

Fig. 4. Cycles number for all fuels at 3000 rpm and 40% engine throttle

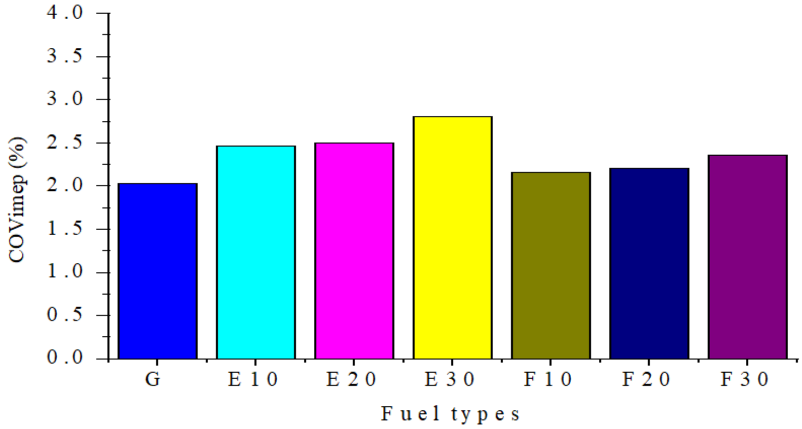

Fig. 5. Maximum COVimep versus fuel type for all fuels for 3000 rpm and 40% engine throttle

Response surface methodology (RSM) was used to optimize the data. It shows that the run order developed at the 27-point number in **Table 3**. Three factors were set in RSM: engine speed, engine throttle and fuel blend, while the responses set are brake power, brake thermal efficiency, brake-specific fuel consumption, nitrogen oxide, carbon monoxide, and hydrocarbon. The best result shows a desirability of 0.833%, close to 1. It shows that a 30% blend of fusel oil at 40% engine throttle and 3000 rpm gives the best result. Analyses of variation (ANOVA) are depicted in **Table 4**. The output model is significant where the p-values are less than 0.05%. It shows that the factor endures a considerable effect at a 95% confidence level. The higher R^2 is 0.9886, which is near to 1, while the desirable and reasonable agreement with Adj R^2 is 0.9843. The lowest value of σ is necessary to attain the fittest model types. Based on R^2 and σ suggested by the design of experiment software, the quadratic and linear model best fits all predicted responses. Adequate precision (AP) is 48.3, which measures the signal-to-noise ratio, and a value greater than 4 is always desirable. Based on ANOVA statistical analysis, the data shows positive results for all responses. **Eq. 1** shows the formula used to calculate the brake power.

Table 3. Experimental design matrix with input factor and responses

Number of run order	Factors			Responses						
	Engine throttles (%)	Engine Speeds (rpm)	Fuel Blends (%)	Bp (kW)	BTE (%)	BSFC (g/kWh)	NOx (ppm)	HC (ppm)	CO (%)	Desirability (%)
1	40.00	3000.00	F30	33.0136	35.0372	285.425	1013.72	185.337	1.59036	0.833
2	40.00	3000.00	E30	32.24	34.0652	291.493	983.622	182.964	1.42998	0.833
3	40.00	2964.22	F30	32.4184	34.777	286.56	1002.68	185.256	1.60554	0.831
4	40.00	2958.71	E30	31.5639	33.7717	292.931	971.286	182.821	1.4476	0.829
5	40.00	2919.56	E30	30.9272	33.4949	294.302	959.669	182.693	1.46368	0.824
6	40.00	3000.00	E20	32.7398	35.0605	278.004	1020.94	189.037	1.75193	0.823
7	40.00	2881.68	E30	30.315	33.2286	295.635	948.499	182.577	1.47866	0.820
8	40.00	2952.86	F20	32.7541	35.4568	269.53	1031.46	190.411	1.87753	0.819
9	40.00	2926.83	F20	32.3193	35.2728	270.416	1023.13	190.365	1.88678	0.819
10	40.00	2904.60	E20	31.1722	34.3796	281.485	991.249	188.774	1.78803	0.816
11	36.68	3000.00	E30	31.1178	32.2665	291.532	959.755	183.227	1.632	0.810
12	40.00	2730.95	F30	28.6252	33.1132	294.1	932.325	184.901	1.69195	0.802
13	40.00	2730.95	F20	29.1083	33.9111	277.18	961.559	190.135	1.9476	0.802
14	40.00	2906.55	E10	31.7567	35.1422	272.625	1034.02	192.239	2.09137	0.797
15	40.00	2918.55	E10	31.9555	35.2271	272.181	1037.82	192.24	2.08763	0.797
16	40.00	2880.62	E10	31.3287	34.959	273.584	1025.85	192.24	2.09928	0.797
17	40.00	2730.95	E30	27.9186	32.1827	301.002	904.764	182.192	1.53259	0.797
18	40.00	2730.95	E20	28.3832	33.1634	287.925	938.364	188.421	1.84445	0.794
19	40.00	2684.61	E30	27.1943	31.8657	302.672	891.544	182.098	1.54735	0.789
20	40.00	2826.95	F10	30.8926	35.167	263.243	1032.27	195.116	2.33071	0.786
21	40.00	2810.44	F10	30.6212	35.0519	263.833	1026.91	195.118	2.33439	0.786
22	40.00	2800.00	F10	30.4505	34.9802	264.209	1023.55	195.12	2.33657	0.785
23	40.00	2730.95	E10	28.8938	33.9143	279.18	979.3	192.313	2.1397	0.785
24	40.00	2730.95	F10	29.327	34.505	266.699	1001.38	195.149	2.35022	0.782
25	40.00	2729.70	G	29.8208	35.1964	257.05	1033.45	200.437	2.48745	0.769
26	40.00	2751.87	G	30.1854	35.3488	256.277	1040.71	200.38	2.48255	0.769
27	40.00	2777.52	G	30.6086	35.5257	255.385	1049.14	200.317	2.47664	0.767

Table 4. ANOVA result for response surface quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	6825.48	23	296.76	226.76	< 0.0001
A-Engine throttle	1039.10	1	1039.10	794.01	< 0.0001
B-Engine speed	5003.91	1	5003.91	3823.67	< 0.0001
C-Fuel blend	9.31	6	1.55	1.19	0.3264
AB	649.25	1	649.25	496.12	< 0.0001
AC	0.51	6	0.085	0.065	0.9989
BC	2.74	6	0.46	0.35	0.9079
A^2	85.32	1	85.32	65.20	< 0.0001
B^2	35.34	1	35.34	27.00	< 0.0001
Residual	78.52	60	1.31		

The first analyses examined the effects of fuel blends, engine throttle and engine speed using different fuels on brake power. Brake power is defined as the power delivered by the engine to the main shaft to produce torque and angular speed [39]. **Table 5** shows the ANOVA results of the response parameter for brake power. The model is significant as R-squared is near to 1. The relation between brake power, engine speed and engine throttle is as mentioned in **Eq. 1**. **Fig. 6** shows the graph of brake power for engine speed and engine throttle. The response surface profile for the quadratic model is shown in (a) scatter graph and (b) 3D graph. Based on the graph it shows that when engine speed and engine throttle increase, the brake power increases.

$$Pb = 15.44 + 4.72 * A + 9.45 * B + 0.58 * C[1] + 0.043 * C[2] - 0.24 * C[3] - 0.51 * C[4] + 0.25 * C[5] + 0.10 * C[6] + 4.57 * AB + 0.11 * AC[1] - 0.042 * AC[2] - 0.090 * AC[3] - 0.19 * AC[4] + 0.10 * AC[5] + 0.069 * AC[6] + 0.38 * BC[1] + 0.030 * BC[2] - 0.21 * BC[3] - 0.34 * BC[4] + 0.14 * BC[5] + 0.091 * BC[6] - 2.27 * A2 + 1.38 * B2 \quad \textbf{(Eq. 1)}$$

Table 5. ANOVA result response for brake power and brake thermal efficiency

Brake Power		**Brake Thermal Efficiency**	
Parameter	**value**	**Parameter**	**Value**
Std. Dev.	1.14	Std. Dev.	0.73
Mean	15.09	Mean	24.03
C.V. %	7.58	C.V. %	3.03
PRESS	176.51	PRESS	63.44
R-Squared	0.9886	R-Squared	0.9868
Adj R-Squared	0.9843	Adj R-Squared	0.9817
Pred R-Squared	0.9744	Pred R-Squared	0.9736
Adeq Precision	48.359	Adeq Precision	58.081

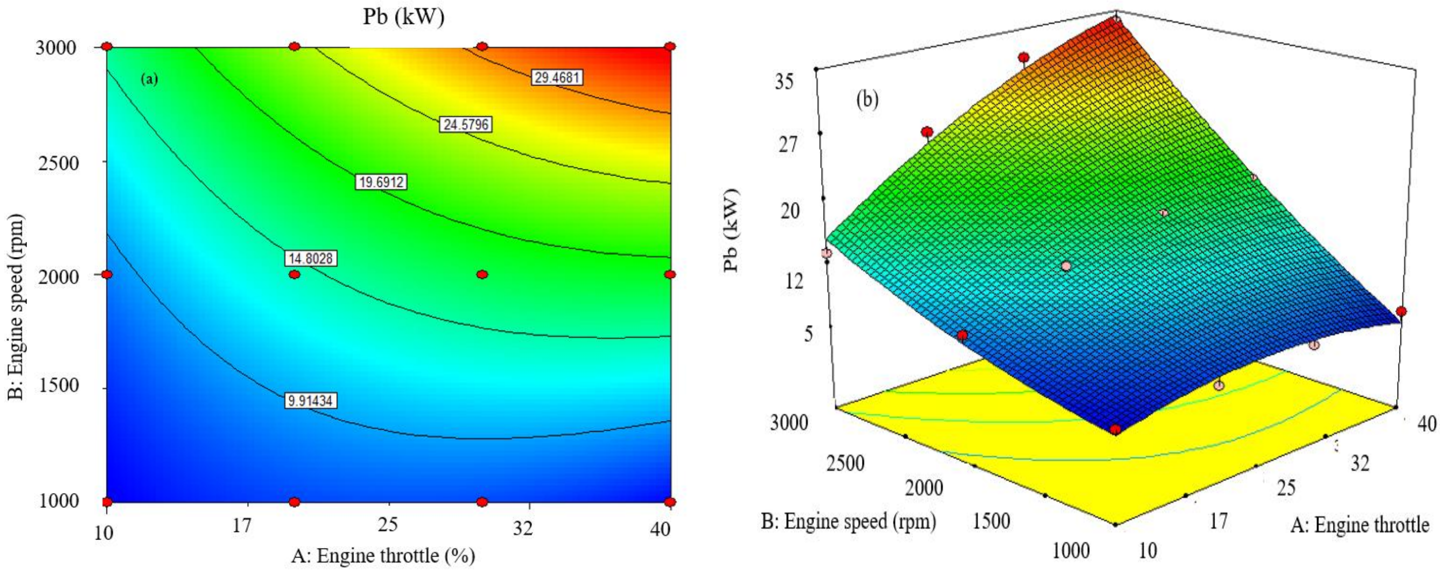

Fig. 6. Graph brake power for engine speed and engine throttle (a) scatter (b) 3D

4. Conclusion

A study on turbocharged engine spark ignition (SI) using ethanol blends and fusel oil as blends with gasoline (RON95) is used to evaluate the engine performance, emission and stability of combustion. Then, all the fuels were measured in terms of physical properties. In addition, the response surface methodology (RSM) was used to optimise the responses and factors. As a further conclusion, the summary of the research findings and the recommendation for future work are presented in this chapter. ANOVA analysis indicates that statistical models are significant with values of Prob > F less than 0.0500. In addition, the R-squared of all data showing values close to 1 contributed to the model being significant. As a result, the 27-run order for desirability close to 1 indicated 0.833% as the best solution. The optimization of the factors, which are engine speed, engine throttle, and fuel blend, are 3000 rpm, 40%, and F30, respectively. Then, the responses that are brake power, brake thermal efficiency, brake specific fuel consumption, nitrogen oxide, hydrocarbon and carbon monoxide showed to be 33.0 kW, 35.0 %, 285.4 g/kWh, 1013.7 ppm, 185.3 ppm and 1.59 % respectively. Using the same factors for the engine retest confirmed the results at 34.5 kW, 36%, 396 g/kWh, 1102 ppm, 197ppm and 1.69 %. The percent of Absolute Error to all responses are Brake Power, Brake Thermal Efficiency, Brake Specific Fuel Consumption, Nitrogen Oxide, Hydrocarbon and Carbon Monoxide which are recorded at 2.9%, 2.8%, 3.7%, 8%, 6% and 5.8% respectively. Indeed, the optimisation result using RSM is suitable for engine speed at 3000 rpm, engine throttle of 40% and fuel blend of fusel oil blend of 30%.

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