Optimization of Performance and Exhaust Emissions of a Spark-Ignition (SI) Engine Fueled with Bioethanol-Gasoline Blends using TOPSIS Methodology

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Abstract. Energy crises and environment impact forced governments and countries to develop utilizing renewable energy in different forms. One of the first forms of alternative energy which was in use is bioethanol which is using in SI (spark ignition) engines as pure fuel or after blending with gasoline. The selection of proper blending of bioethanol plays an important role in the production of alternative energy. In this investigation, the use of TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) to select the optimal value of the engine performance and exhaust pollutants which run at various bio-ethanol-gasoline fuel blends, namely E5, E10, E15 and E20. Obtained results indicate that performance parameters (i.e. torque, power) for different bioethanol-gasoline blends improved. It is evident from results that there is an increase in NOX as well Carbon dioxide (CO2) emission while UBHC and CO decreased. TOPSIS methods indicate that a mixture ratio equal to 20% (E20) and an engine speed equal to 3000 rpm were chosen to be optimal working condition.

Keywords: energy, exhaust emissions, fuel, performance, pollutants

1. Introduction

Energy saving is one of the most effective issues for strategic planning in the industrialized world [1–3]. On the other hand, the demanding energy is clearly a driving force of the industry and world economy. [4] Among different types of energy, the fossil energy is the largest source of world energy which is currently used in internal combustion engines [5]. One of the most profitable options for governments to replace conventional fossil fuels in is the use of renewable fuels including biodiesel, bioethanol, bio methanol, biogas, etc. [6].

Bioethanol, which is extracted from sugar and starch feedstock, can be used alone or blend with gasoline in SI engines without the need to any major modification in the engine [6–8]. Using bioethanol–gasoline blends in spark ignition engines improves engine performance and reduces emissions [9–12]. Due to the complexity of issues associated with internal combustion engines, it is difficult to model using one decision modeling [13–17]. Therefore, the use of modeling techniques in combination with experimental methods provides a lot of benefits for understanding these phenomena [3,14,18]. There are many research works deal with predicting engine parameters fueled with bio-based additive [19].
In a number of studies, artificial neural networks (ANNs) have been used to predict engine performance and emissions. For instance, Najafi et al. [20] analyzed the engine performance and pollutants of a four-cylinder SI engine operating on ethanol–gasoline blends of 5%, 10%, 15% and 20% with the aid of ANN model. An ANN model was developed to predict engine performance and exhaust emissions. Their results showed that with increasing brake thermal efficiency and the volumetric efficiency (VE), the brake specific fuel consumption (BSFC) was declined. Although, the condensation of CO2 and NOx were increased with increase the amount of bioethanol. In an experimental work, Kiani et al. [21] used artificial neural network (ANN) modeling for predicting of performance and exhaust emissions in a spark ignition engine fueled with different ethanol- gasoline fuel blends. They used experimental results for training and validating. Their results proved that ANN demonstrated the best accuracy in predicting the emission characteristics, engine brake power (BP) and torque.

Najafi et al. [22] studied the influence of five different blends of ethanol- gasoline on the performance and exhaust emission parameters of a four-cylinder spark ignition engine using response surface methodology (RSM). Their results proved that design of experiments (DOE) based on RSM has many advantages in modeling of engine performance. A mixture consists of 10 % ethanol (E10) were identified as best blend with highest desirability. A number of investigators have developed novel techniques for modeling of spark ignition (SI) engines. For instance, Najafi et al. [23] proposed a comparison of both ANFYS and support vector machines (SVM) model for prediction of engine performance and gaseous exhaust emissions of a SI engine with various bioethanol ratios and validates models with experimental test results. Their results demonstrated that the machine learning based on ANFIS –SVM techniques has great advantages for modeling engine application and emissions using alternative fuels. They also mentioned that the ANFIS technique is much efficient than SVM method.

In an interesting study, Cay et al. [24] strived to model the performance (i.e. BSFC, torque, pe, APe) and emissions (i.e. CO, HC) characteristics of a four-stroke spark-ignition engine with blend of methanol-gasoline fuel by exerting ANN method. Their finding showed that logsig (logistic sigmoid) algorithm provide the best accuracy statistics (R) for the designed network. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is based on multi-criteria decision analysis which was introduced by Hwang and Yoon in 1981[25]. This method is a relatively simple and quick method for analyzing and monitoring the best strategy [15,26]. In an isolated study, ANN modeling followed by multi-objective optimization (MOP) was used to finding the best solution of the engine performance and emissions of the CI engine fueled with conventional petro diesel and castor oil biodiesel blends. They explain that, applying a hybrid method of NSGA-II integrated with TOPSIS design provides some trade-off optimum points on the non-dominated solutions which can be used for achieving high performance [25]. Dehghani Soufi et al. [27] conducted experiment on the use of TOPSIS techniques for choosing the best performance with more desirability reported that the palm bio-lubricant illustrated better performance in comparison with the mineral two-stroke lubricants.

It is needless to mention that, there is rarely study on the application of TOPSIS to select optimal ethanol blend based on the engine working condition and emission characteristics using TOPSIS technique. Hence, in this paper tried to evaluate the best appropriate blend and engine working conditions by using TOPSIS techniques. To implement the experimental tests was used to evaluate engine parameters and then TOPSIS analyzing method was applied to optimize and sort for all test results based on the improvement of engine parameters. In this paper, TOPSIS is proposed as the most effective method to evaluate the optimal blend and engine working condition.

2. Material and Methods

2.1. Description of the experimental setup

In this experimental work, four-cylinder naturally aspirated, water-cooled SI gasoline engine KIA 1.3 SOHC was used. The technical characteristics of the engine are shown in Table 1.
Table 1. Technical specifications of the test engine.

| Type of engine | SI engine, 4 cylinder, water cooled |
|----------------|-----------------------------------|
| Bore×Stroke(mm) | 71.0×83.6 |
| Engine displacement volume (cc) | 1323 |
| Compression ratio | 17.5 |
| Maximum Torque (Nm-rpm) | 410-1300 |
| Maximum Power (kW-rpm) | 47-2300 |

Exhaust gas emissions were measured by means of AVL DIGAS exhaust gas analyzer. Spark advance was set to 25 before TDH (top death center). Engine performance parameters and gas emissions have been determined for gasoline at the compression ratios (CR) of 9.7. An eddy current dynamometer which is a SCHENCK WT190 brand is capable of absorbing 190 kW at 10000 rpm engine speed. Dynamometer was equipped with a barometer to determine the pressure inside the cylinder chamber. The data collected from the pressure sensor is recorded in the dynamometer control unite. AVL Flowsonix air flow meter was used to determine air consumption. The consumption rate of fuel was quantified with a Pierburg laminar-type flow meter. A Distributor-Less Ignition (DLI) was employed for ignition apparatus. An Ignition system was Semi-static distributor less ignition (DLI) was used as. The schematic view of test setup is depicted in Figure 1. Instruments accuracies and parameter uncertainties are illustrated in Table 2.

Figure 1. System configuration for engine testing (a) substantive and (b) schematic.

Table 2. The accuracies of the measurements in the calculated parameters.

| Instrument variables       | Accuracy (±) |
|----------------------------|--------------|
| Engine speed (rpm)         | 2.00         |
| Engine load (N)            | 0.1          |
| Fuel Consumption (g)       | 0.1          |
| Temperature (°C)           | 0.1          |
| Time                       | 0.5          |
| Emissions parameters       | Uncertainty (%) |
| UHC                        | 1.80         |
| CO2                        | 2.40         |
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| Performance variables | Uncertainty (%) |
|-----------------------|-----------------|
| Brake power (B.P)     | 1.03            |
| Torque                | 1.10            |
| BSFC                  | 1.10            |

In this study, a continuous solid fermentation setup based on fermentation of sugar has been employed for producing bioethanol from inedible potato biomass. The specifications of potato-based bioethanol are cited in Table 3:

**Table 3.** Characteristics of ethanol-gasoline blended fuels.

| Specification                  | Tested fuel | Standard |
|--------------------------------|-------------|----------|
| Density (kg/m3)                | E5          | ASTM D 4052 785 |
| Viscosity (cSt)                | E10         | ASTM D 88 1.1 |
| Calorific value (kJ/kg)        | E15         | ASTM D 240 27000 |
| Octane number                  | E20         | ASTM D 2699 108.6 |
| Pour point (°C)                | E5          | ASTM D 97 -50< |
| Flash point (°C)               | E10         | ASTM D 93 -14 |

In this investigation, potato biomass has been considered as a bioethanol source. Various blends of ethanol and gasoline including E5, E10, E15, and E20 were examined. Since engine could not run normally at higher ethanol ratios, therefore, experimental data obtained up to E20 (80% gasoline - 20% ethanol) not presented. The characteristics of blended fuels are presented in Table 4.

**Table 4.** characteristics of ethanol-gasoline blended fuels.

| Fuel Specification | Tested fuel | Standard |
|--------------------|-------------|----------|
| Vapor Pressure (kPa)| E5          | 55.16    | ASTM-D323 |
|                    | E10         | 55.16    |          |
|                    | E15         | 55.16    |          |
|                    | E20         | 55.16    |          |
| Octane number      | E5          | 89.7     | ASTM-D2,699 |
|                    | E10         | 93.8     |          |
|                    | E15         | 95.6     |          |
|                    | E20         | 99.4     |          |
| GHC (MJ/kg)        | E5          | 44.15    | ASTM-D340 |
|                    | E10         | 40.15    |          |
|                    | E15         | 38.6     |          |
|                    | E20         | 40.51    |          |

Experimental study done for various blends in various days, but for all tests is done in one day for each blend. Correction factors are calculated and used to correct results for comparing together. Test variables and conditions were controlled. Test pattern for all blends is the same. Engine speed is varying from 1000 to 5000 rpm in 500 rpm steps. In each rpm level, output parameters including torque (Nm), power (kW), CO (% Vol.), CO2 (% Vol.), UBHC (ppm), NOX (ppm), specific fuel consumption (SFC) and volumetric efficiency (VE) are recorded.

2.2. **Optimization based on TOPSIS.**

2.2.1. **Normalization matrix.** In this experiment data obtained in different scale and order. In addition, the recorded data must be homogenized so that they can be compared and use together. After that, the data have been normalized in the form of matrix using Equation (1):
\[ n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \]  

In this equation \( n_{ij} \) refer to evaluation matrix. Other parameter (i.e. \( i, j \)) are matrix index.

2.2.2. Weighted normalized decision matrix. Weighted matrix is used to show the importance of parameters. Weigh of each parameter is determined between 0 and 1. The sum of all of weigh is equal to 1. In this study we used ENTROPY method for weight calculation. The corresponding value is defined as follows in equation (2) to (6). Where \( p_{ij}, K, E_j, d_j \) and \( W_j \) are:

\[ p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} ; \quad j = 1, \ldots, n \quad \forall_{ij} \]  

\[ K = \frac{1}{\ln m} \]  

\[ E_j = -K \sum_{i=1}^{m} p_{ij} \ln p_{ij} \quad \forall_{j} \]  

\[ d_j = 1 - E_j \]  

\[ W_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad \forall_{j} \]  

2.2.3. Positive and negative ideal solution. The positive ideal solution (PIS) shows the most preferable option and the negative ideal solution (NIS) shows the least preferable option. PIS is maximum option for parameters which in bigger case is better. And minimum for which in lower case is better. PIS is an alternative and that is the minimum option for parameters which in bigger case is better. And maximum for which in lower case is better. Using equation (7) and (8), calculate the separation from PIS and NIS for each parameter. The relative closeness to the ideal solution for each parameter is calculated using equation (9). Using the relative closeness to the ideal solution, increasing of the relative closeness to the ideal solution is more preferable.

\[ S_{i^+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v^+_{ij})^2} \]  

\[ S_{i^-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v^-_{ij})^2} \]  

\[ C_{1^+} = \frac{S_{1^-}}{S_{1^+} + S_{1^-}} \]  

3. Results and Discussion
In this section, the data have been analyzed and sorted using TOPSIS methodology. Parameters and test points were arranged based on benefit and favor methodology. These data are sorted based on the ethanol- gasoline fuel blend, engine speed and output parameters including torque, power, specific fuel consumption, volume efficiency and emission i.e. CO, CO\(_2\), O\(_2\), UBHC and NOX. Experimental results
are shown at different engine speed for various fuel blend in Figures 3 to 9. Figure 2 indicates the effect of engine speed on the engine torque. It can be observed that engine torque increases with increase in engine speed for all fuel blend ratios. According to Figure 2, increasing in engine speed lead to less torque. The decline in peak torque at high speeds was because of a decrease in time for filling the cylinder chamber. Hence, cylinder pressure decreases slightly when reducing the volumetric efficiency (VE) \[22,28–30\]. Figure 3 shows the variation of engine brake power (BP) with engine speed for various fuel blend ratios. Figure 3 clearly shows that increase in the percentage of biethanol (i.e. less proportion of gasoline) increase drastically the brake power of the engine at all tested fuel proportions. Additionally, an increase in engine power corresponds to the increment in the indicated mean effective pressure (IMEP). This can be attributed to the fact that by increasing proportion of bioethanol, volumetric efficiency increase due to high density of the mixture. One of the distinct advantages of ethanol is promote complete combustion, therewith increasing the engine brake power and torque. \[31,32\]

\[\text{Figure 2. Variation of torque with engine speed for different test fuel blends.} \]

\[\text{Figure 3. Variation of engine power with engine speed for different test fuels.} \]

Carbon monoxide (CO) emission as a function of engine speed for different bioethanol fuel blends is shown in Figure 4. As seen in this figure, a decrease in CO emission was observed when the percentage of bioethanol in blend increase. The variation of the CO\(_2\) emission versus engine speed for different blends is presented in Figure 5. It is clearly understood from Figure 5 that CO\(_2\) formation increases while the bioethanol ratio increases as well as engine speed. Generally, CO\(_2\) forming related with both stoichiometric ratio and CO emission concentration. On the other hand, increasing bioethanol ratio causes a lean burning and improvement in the combustion process, resulting in increase of the CO\(_2\) emissions.[33,34]

\[\text{Figure 4. Effect of ethanol blend on CO emission at various engine speeds.} \]

\[\text{Figure 5. CO\(_2\) emission vs. engine speed for various test fuels.} \]
Figure 6 depicts the variation of UHC emissions for each engine speed and bioethanol concentration. UHC emissions decreased using bioethanol in blend of gasoline due to lower in-cylinder temperatures. As shown in this figure, when bioethanol blends were increased UHC emissions was decreased. The formation of UHC as unburned fuel component increases with increase in air-fuel ration. The reason for reduction of UHC emission at high bioethanol blends would be attributed to fuel oxygen content promoting complete combustion, the same as the CO concentration [35,36]. Figure 7 illustrate the relationship between the NOx concentration and engine speed for various bioethanol ratios. As shown in test results, increasing ethanol, results increasing NOx which is because of increasing in temperature [37,38]. This effect is the only negative effect of ethanol increasing in blend. However, the higher oxygen content in the mixture and lower cetan number promote the NOx formation. Increasing engine speed, improves most of parameters including power, CO2, NOx, and has negative effect on fuel consumption and CO. For this reason, positive effect of engine speed is more than negative effect and increasing in engine speed increase improvement. In fact, ethanol and engine speed have a super position effect and improvement with increasing in these factors is predictable. Of course, if choose another method in weight matrix calculation, and using different weighted matrix can change this results totally. Based on the goals and purpose of users, parameter’s weight can change and affect weighted matrix and final results definitely will be different.

**Figure 6.** Effect of engine speed on UHC emission for various fuel blends.

**Figure 7.** NOx emission vs. engine speed for different test fuels.

Figure 8 shows that specific fuel consumption (SFC) increase by ethanol increasing in blend, however, this amount is not high. Energy content of ethanol is lower than gasoline; normally we use more ethanol for going same distance regarding gasoline.

**Figure 8.** Variation of specific fuel consumption w.r.t engine speed for bioethanol blends.
3.1. **Optimization based on TOPSIS.**

The TOPSIS methodology is used for determining the best ethanol-gasoline blend. The decision matrix which is built by test results data, analyzed by using TOPSIS method and related equations. The first TOPSIS algorithm step is calculating normalized matrix which results are shown in table 5 for all test point and data. PIS and NIS index are calculated for test parameters using weighted matrix and shown in table 5. In next step, S+ and S- value are calculated for all parameters and test point.

**Table 5. PIS and NIS index.**

|       | S (rpm) | T   | P       | F       | A       | CO     | CO₂    | HC     |
|-------|---------|-----|---------|---------|---------|--------|--------|--------|
| PIS   | 0.00016 | 0.009027 | 3.79365E-06 | 0.003633 | 0.01016 | 3.2E-06 | 0.000492 | 0.001289 |
| NIS   | 0       | 0   | 0.000135623 | 0.120465 | 0.225358 | 4.52E-06 | 3.73E-05 | 0.144414 |

The relative closeness at different engine speed for various fuel blends are shown in Figure 9. According to Figure 9, increasing ethanol in blends is definitely preferable and increase engine performance. Figure 10 shows the relative closeness versus fuel blend for different engine speed. It is revealed from the results that engine performance increases with increasing engine speed and ethanol blends.

![Figure 9](image.png)

**Figure 9.** The relative closeness at different engine speed for various fuel blends.

![Figure 10](image.png)

**Figure 10.** The relative closeness at various...
The distance to the good point is higher and relative closeness is very low particularly in lower engine speed. 3D schematic of the relative closeness is shown in Figures 11 and 12. Preferable points on the test are located in the top of the graph. With increasing ethanol blends exhaust gas temperature and engine power increases while CO$_2$, CO and UBHC decreased. Based on TOPSIS methods results, optimal value of engine speed and ethanol-gasoline ratio were obtained 3000 rpm and 20% ethanol in blend fuel (E20).

![Figure 11. 3D schematic of the relative closeness at various fuel blends for different engine speed.](image1)

![Figure 12. 3D schematic and contour of the relative closeness at all test points.](image2)
4. Conclusions
In this investigation, experimental studies of using gasoline-ethanol blends including E0, E5, E10, E15 and E20 and comparison between various blends are carried out. Using TOPSIS analyzing method, the results sorted and ranked to improve performance of the engine. The obtained results are summarized as below:

- With increasing bioethanol ratio, torque, pressure and NOx increased.
- Carbon monoxide, HC, and carbon dioxide reduced as bioethanol in blend increase.
- TOPSIS methods indicate that with increasing ethanol in blend and engine speed, engine performance will approve.
- TOPSIS methods indicate that engine rotational speed and ethanol percentage are 3000 rpm and 20% (E20), respectively, for optimal working conditions.

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