LAUTECH Journal of Engineering and Technology 18 (3) 2024: 169-178
10.36108/laujet/4202.81.0371

Evaluation of performance parameters of direct injection spark ignition engines fuelled with alcohol-gasoline blends

[1*]Aderibigbe A. A., [1]Okekunle P. O., [2]Alade A. O., [1]Adewoye S. O. and [1]Folorunsho T. A.

[1]*Department of Mechanical Engineering, Ladoke Akintola University of Technology, P.M.B.4000, Ogbomoso, Oyo State, Nigeria.*
[2]*Department of Chemical Engineering, Ladoke Akintola University of Technology, P.M.B.4000, Ogbomoso, Oyo State, Nigeria.*

Article Info

Article history:

Received: Sept 5, 2024
Revised: Oct 3, 2024
Accepted: Oct 8, 2024

Keywords:

Direct Injection Spark Ignition Engines, Alcohol-Gasoline Blends, Engine Performance, Brake Specific Fuel Consumption and Brake Thermal Efficiency.

Corresponding Author:
aaaderibigbe@lautech.edu.ng

ABSTRACT

This study evaluated the performance of Direct Injection Spark Ignition (DISI) engines fuelled with alcohol-gasoline blends under varying engine loads and speeds, focusing on the blends of methanol, ethanol, butanol and gasoline. Experimental tests were conducted using a single-cylinder DISI engine under controlled laboratory conditions. Pure gasoline and two alcohol-gasoline blends were tested at different engine loads (0%, 50%, and 100%) and speeds (2500, 3000 and 3500 RPM). D-optimal design in Response Surface Methodology (RSM) of Design-Expert (version 13.0.1) was used to design the experiments and mathematical models were also formulated for the performance parameters considered. The adequacy of the models was determined by using statistical tests and the best-fit model for each response was selected. Analysis of Variance was also done for a better understanding of the model's attributes. Results showed that alcohol-gasoline blends have the potential to improve the combustion efficiency of DISI engines. The thermal efficiency of the optimum alcohol-gasoline blend was higher than that of pure gasoline by 0.9%. The addition of alcohols led to an increase in Brake Specific Fuel Consumption (BSFC) by 1.89% and engine torque exhibited a marginal improvement. Alcohol-gasoline blends can serve as viable solutions to meet the future sustainable energy supply goals in the automotive industry.

INTRODUCTION

The increasing demand for energy and growing concerns about environmental pollution have pushed the automotive industry toward alternative fuels that can reduce both fuel consumption and harmful emissions. Among the various alternatives, alcohols, particularly ethanol and methanol, have gained a significant attention as fuel additives in gasoline-powered internal combustion engines. Their renewable nature, high oxygen content, and cleaner combustion characteristics make them attractive choices for improving the performance and environmental sustainability of gasoline engines, especially Direct Injection Spark Ignition (DISI) engines (Zhang *et al*., 2022; Elshenawy *et al*., 2023).

DISI engines, known for their improved fuel efficiency and power output, have become a widely adopted technology in modern vehicles. These engines combine the benefits of direct fuel injection with spark ignition, which allows for a better control over fuel-air mixture and combustion timing, leading to enhanced performance and reduced emissions. However, the direct injection mechanism also poses challenges, such as increased particulate matter formation, especially when using traditional gasoline fuels (Zhou *et al*., 2016). The use of alcohol-gasoline blends is seen as a potential solution to these challenges, as alcohols have lower carbon content and higher volatility, which can promote cleaner combustion (Liu *et al*., 2018).

While alcohol-gasoline blends offer several advantages, there is a need for a comprehensive evaluation of their effects on the performance parameters of DISI engines. Most of the existing studies have focused on the emissions benefits of alcohol fuels, but there are limited data on how methanol-ethanol-butanol gasoline blends affect engine performance under real-world operating conditions. Specifically, the impact of ethanol and methanol blends on fuel consumption, thermal efficiency, and power output in DISI engines requires further exploration (Ahmed *el al*., 2021; Akbiyik *et al*., 2023).

Additionally, the use of alcohol-gasoline blends may present challenges related to engine durability and long-term performance. Alcohols are known to be less energy dense than gasoline and may require more quantity to produce the same mechanical work. Therefore, understanding the trade-offs between improved performance and potential mechanical issues is essential for assessing the viability of these fuels in modern engines (Costa *et al*., 2021; Jiahong *et al*., 2022).

This study aims to evaluate the performance parameters of DISI engines when fuelled with various alcohol-gasoline blends. These blends are compared with pure gasoline by assessing their effects on key engine performance metrics, including brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and engine torque. Understanding the impact of these blends on engine performance is crucial for determining their feasibility as alternative fuels in the automotive sector (Heywood, 2018; Zutta *et al.*, 2020).

The significance of this research lies in its potential to contribute to the development of cleaner and more efficient fuel options for the automotive industry. Alcohol-gasoline blends represent a promising solution for the future of internal combustion engines, particularly in DISI applications (Karagoz *et al*., 2021). Furthermore, the findings from this study will provide valuable insights for automakers and fuel manufacturers, helping them to optimize fuel formulations and engine designs for enhanced performance and environmental friendliness. By understanding the trade-offs between different alcohol-gasoline blends, this research will support the ongoing transition towards cleaner, more sustainable transportation technologies.

MATERIALS AND METHODS

Materials

The materials used in this study included methanol, ethanol and butanol, with purity of 99.9%, procured from SAVIDEB Chemical Enterprise, Osogbo, Osun state. Gasoline was obtained at a petrol filling station in Aroje area of Ogbomoso, Oyo state.

Blending

Alcohol-gasoline blend ratios were determined using the D-optimal Design in Mixture Methodolgy of Design Expert Software (version 13.0.1). Methanol, ethanol, butanol and gasoline were measured with different measuring cylinders and poured into a beaker. The mixture was then agitated vigorously to make a homogenous blend. Two alcohol-gasoline blend samples were selected for use in the experiments, based on their physicochemical and fuel properties, which were the optimum blend (9.859% methanol, 5.0% ethanol, 5% butanol and 80.141% gasoline) and Blend-13 (5% methanol, 5% ethanol, 5% butanol and 85% gasoline). Pure gasoline was used as control.

Experimentation and modelling

A four-stroke, single-cylinder DISI engine was connected to a hydraulic dynamometer with a coupling, and the set-up was mounted on a rigid frame for the experiment. The hydraulic dynamometer (TD 115) was connected to an instrumentation unit (TD 114) designed to stand beside the engine under test. The instrumentation unit has a tachometer for measuring speed in rpm, torque meter for measuring torque in Nm, thermometer for measuring exhaust gas temperature, fuel measurement tube for measuring fuel consumption and airflow manometer for measuring air consumption. Stopwatch, thermometer, barometer, vibrometer and noise meter were used in conjunction with the TD 114 instrumentation unit.

D-optimal Design in Response Surface Methodology of Design Expert software (version 13.0.1) was used to generate the factors combinations for the DISI engine, making use of engine speed (2500, 3000, and 3500 r.p.m.) and engine load (0, 50 and 100%) as factors, resulting in a total of eleven runs. The DISI engine was then in turn fuelled with pure gasoline (PG), optimum blend (OB) and Blend-13 (GB). The performance of the engine was then determined in each case by evaluating Brake Specific Fuel Consumption (BSFC), Brake Power (BP), thermal efficiency, torque, Exhaust gas temperature (T_{EG}), engine vibration and engine noise. D-optimal design under the Response Surface Methodology (RSM) in Design Expert 13.0.1 software was adopted for model development and analysis of data.

i. BSFC

BSFC is the fuel mass flow rate ($\dot{m}_f$) divided by the engine brake power (BP), as given by equation 1,

$$BSFC = \frac{\dot{m}_f}{BP} x - 3600 \qquad 1$$

Where: $\dot{m}_f$(g/s) is Fuel mass flow rate and BP(KW) is effective brake power

But BP = $T_e W_e$

$$\therefore \text{BSFC} = \frac{\dot{m}_f}{T_e W_e} \qquad 2$$

Where T_e is effective engine torque, and W_e is engine speed

$$T_e = \text{Force} \times \text{distance} \qquad 3$$

Where Force is the product of the mass hung on the torque arm of the dynamometer and acceleration due to gravity (g) while distance is the torque arm of the dynamometer.

(ii) Engine torque

Engine torque (Nm) can be defined as a function of the engine's brake mean effective pressure (BMEP) as given by Equation 4

$$T_e = \frac{N_C V_d BMEP}{2\Pi n_r} \qquad 4$$

Where N_C is the number of cylinders, V_d is the cylinder displacement volume and *BMEP* is the brake mean effective pressure.

n_r is number of crankshaft rotations Equation 4 was substituted into Equation 2 and yielded Equation 5, given as

$$BSFC = \frac{2\Pi n_r m_f}{N_c v_d BMEP w_e} \qquad 5$$

The lower the BSFC, the more efficient the engine.

(iii) Thermal efficiency

The thermal efficiency was calculated as a function of BSFC and LHV given as equation (6, 7)

$$\eta_{Th} = \frac{1}{BSFC.LHV} \qquad 6$$

But $\frac{1}{BSFC} = \frac{BP}{\dot{m}_f}$

$$\therefore \eta_{Th} = \frac{BP}{\dot{m}_f.LHV} \qquad 7$$

Where: η_{TH} = Thermal efficiency and LHV = lower heating value.

(iv) Measured parameters

Brake Power (BP) and engine torque were measured by the instrumentation unit attached to the dynamometer. The exhaust gas temperature (EGT) of the DISI engine was measured by a chromel alumel thermocouple thermometer conforming to British Standard (BS1827). The vibration level was measured using a vibration meter (VB-8206SD). The engine noise was measured by a sound level meter (pulse Nova model 46).

RESULTS AND DISCUSSION

The effect of engine speed and engine load on the performance of the DISI engine is presented in this section for pure gasoline (PG), optimum alcohol-gasoline blend (OB) and Blend-13 (GB). Figures 1 shows that BSFC values of 233.6, 221.7 and 230.4 g/kWh were obtained at engine speeds of 2500, 3000 and 3500 rpm respectively for pure gasoline. The lowest value for BSFC was obtained at an engine speed of 3000 rpm. This was due to the fact that volumetric efficiency and engine friction increased with increase in engine speed up to 3000 rpm, above which engine friction dominates. This result agrees with the results obtained by Zhou *et al.* (2016) and Elshenawy *et al.* (2023) and they follow the same trend.

Pure gasoline gave the lowest value of 221.7 g/kWh at an engine speed of 3000 rpm and engine load of 0% while the optimum blend gave 225.9 g/kWh, amounting to 1.89% increase in BSFC for the optimum blend compared to pure gasoline. This may be due to the lower heating value of alcohol-gasoline blends compared to pure gasoline. This result is in agreement with the results obtained by Biswal *et al.* (2020). These findings also agree with the trend of the results of Zutta *et al.* (2020), who modelled the combustion and emission of SI engines fueled with ethanol-gasoline blends.

BSFC increased with an increase in engine load for pure gasoline and the alcohol-gasoline blends considered. The lowest value was obtained at engine load of 0% and the highest value was obtained at engine load of 100% for the three fuels. This is due to the fact that at higher loads, the engine often operates at a richer air-fuel mixture to prevent knocking (pre-ignition). A richer mixture means more fuel is being burned for the same amount of air, leading to less efficient combustion and increased specific fuel consumption. This result is in agreement with the results obtained by Karagoz *et al.* 2021.

Figures 2 shows that an engine speed of 2500 rpm gave the lowest value of 5.95 kW for BP and this value increased to a maximum of 6.37 kW at 3000 rpm and then decreased to 6.15 kW when speed further increased to 3500 rpm. BP increased with an increase in engine load for the three fuel samples considered. This was because as the engine load increased, more fuel was injected into the combustion chambers. The combustion of this additional fuel produced more energy, which increased the pressure on the pistons during the power stroke. This increase in pressure led to a higher torque output, directly increasing the brake power. Pure gasoline gave the maximum BP value of 6.37 kW while the optimum blend gave the highest value of 6.34 kW, which is a marginal reduction of 0.471% at a speed of 3000 rpm and load of 100%. This decrease may be due to the lower heating values of alcohol-gasoline blends. The minimum value of 2.09 kW was obtained for the optimum blend at a speed of 2500 rpm and a load of 0%. This result is in trend with the findings of Iliev (2021), who investigated the effect of ethanol and methanol blending with gasoline on engine performance.

It can be seen from Figures 3 that EGT increased with an increase in engine speed and engine load. The minimum EGT value of 270 ºC was obtained for pure gasoline at a speed of 2500 rpm and a load of 0% while the maximum value of 798 ºC was obtained for the optimum blend at a speed of 3500 rpm and engine load of 100%. This was due to the improved combustion process as a result of the oxygen content of alcohol-gasoline blends. This result is in agreement with the result obtained by Siwale and Bereczky (2018). Similar trend was obtained by Ahmed *et al.* (2021) and Li *et al.* (2017).

Figures 4 shows that engine torques of 22.54, 20.05 and 16.64 Nm were obtained at engine loads of 0, 50, and 100%, respectively. There was a marginal difference in the values of torque obtained for the three blends considered in this study. The maximum value of 22.54 Nm was obtained for pure gasoline while a value of 22.51 Nm was obtained for the optimum blend which is a reduction of 0.13%. This decrease may be due to the lower heating values and higher viscosity of alcohol-gasoline blends. The results obtained are in agreement with the findings of Karagoz *et al*. (2021).

It can be seen from Figure 5 that a maximum thermal efficiency of 41.1% was obtained for optimum blend and a value of 40.2% was obtained for pure gasoline at engine speed of 3000 rpm and engine load of 100%. This implies that the thermal efficiency of the optimum blend increased slightly by 0.9% compared with that of pure gasoline. The minimum value of 25.6% was obtained for pure gasoline. This was due to the oxygen content of alcohol fuels and their higher heat of vapourisation. The results obtained agreed and followed the same trend as those obtained by Ahmed *et al*. (2021) and Costa *et al.* (2021).

Figures 6 and 7 show that engine vibration and engine noise increased with increase in both engine speed and engine load. The maximum engine vibration of 413 Hz and engine noise of 94 dB were obtained for optimum blend while a value of 403 Hz and 93 dB were obtained for pure gasoline at an engine speed of 3500 rpm and engine load of 100 %. This means that engine vibration and engine noise obtained for the optimum blend increased by 2.42% and 1.06%, respectively, compared to pure gasoline. This was due to the oxygen content and higher latent heat of evaporation of alcohol-gasoline blends which increased the rate of pressure rise (dp/dt) and peak pressure values in the engine cylinder during the combustion process. These results are in agreement with the findings of Elshenawy *et al.* (2023) and Lius *et al.* (2023).

The effect of engine speed and engine load on the performance characteristics (seven performance parameters and three exhaust gas emission parameters) of the DISI engine was evaluated. The models developed (given by equations 8-14), in which six are quadratic and one is linear, are in terms of coded factors. The quality of the models developed was evaluated based on statistical methods and experimentation.

$$\text{BSFC}=250.52A + 22.72B - 0.2351AB + 11.58A^2 - 0.62B^2 \quad 8$$

$$\text{BP}=5.18 + 0.0989 A + 1.92 B - 0.0009AB - 0.2822A^2 - 0.7872B^2 \quad 9$$

$$\text{EGT}=670.76 + 20.47A + 222.14B - 0.9574AB + 3.86A^2 - 111.14B^2 \quad 10$$

$$\text{Torque}=16.41 - 2.03A + 6.19B - 1.08AB - 0.5453A^2 - 2.52B^2 \quad 11$$

$$\text{Thermal Efficiency} =35.96 + 1.11A + 4.96B - 0.1872AB - 3.24A^2 - 0.0915B^2 \quad 12$$

$$\text{Engine Vibration}=35.92 + 15.38A + 58.55B - 2.57AB - 2.57AB - 1.38A^2 - 30.88B^2 \quad 13$$

$$\text{Engine Noise} = 80.59 + 3.78A + 9.45B \qquad 14$$

Where A is the engine speed and B the engine load

Quadratic models were obtained for BSFC, BP and EGT with R^2 values of 0.9987, 0.9999 and 0.9999, respectively (Table 1). The predicted R^2 values of 0.9859, 0.9994 and 0.9990 for these parameters are in agreement with their corresponding adjusted R^2 values of 0.9974, 0.9998 and 0.9997, since the difference between adjusted R^2 and predicted R^2 is less than 0.2. High Adeq. Precision values of 80.327, 254.3910 and 192.1021 which are greater than 4 for BSFC, BP and EGT, respectively imply that the signal is adequate and the developed model can be used to navigate the design space. The low values of C.V. and standard deviation mean the model is accurate and can be used for the prediction of these parameters.

Table 1 shows that quadratic models are suggested for torque, thermal efficiency and engine vibration while the linear model is suggested for engine noise with R^2 values of 0.9988, 0.9921, 0.9978 and 0.9944, respectively. The high R^2 value indicates that the data fits the regression model very well. Their predicted R^2 values are in reasonable agreement with their corresponding adjusted R^2 values since the difference between them is less than 0.2. The Adeq. Precision values that measure the signal-to-noise ratio for these parameters which are far greater than 4 indicate that the signal is adequate and the model is reliable. The low values of C.V. and standard deviation obtained for these parameters imply that the models are accurate.

Table 1: RSM model summary statistics and Analyses of Variance (ANOVA) for the performance parameter of DISI Engine

Properties	**BSFC**	**BP**	**EGT**	**Torque**	**Thermal Efficiency**	**Engine Vibration**	**Engine Noise**
Model	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic	Linear
R^2	0.9987	0.9999	0.9999	0.9988	0.9921	0.9978	0.9944
Adj-R^2	0.9974	0.9998	0.9997	0.9975	0.9842	0.9956	0.9930
Pred R^2	0.9859	0.9994	0.9990	0.9915	0.9436	0.9815	0.9879
Adeq Precision	80.327	254.3910	192.1021	77.2157	30.1246	49.9818	63.2527
C.V.	0.3958	0.5569	0.6269	2.18	2.01	1.20	1.02
F- Value	781.40	12996.83	7763.55	811.00	125.49	453.54	707.38
P- Value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

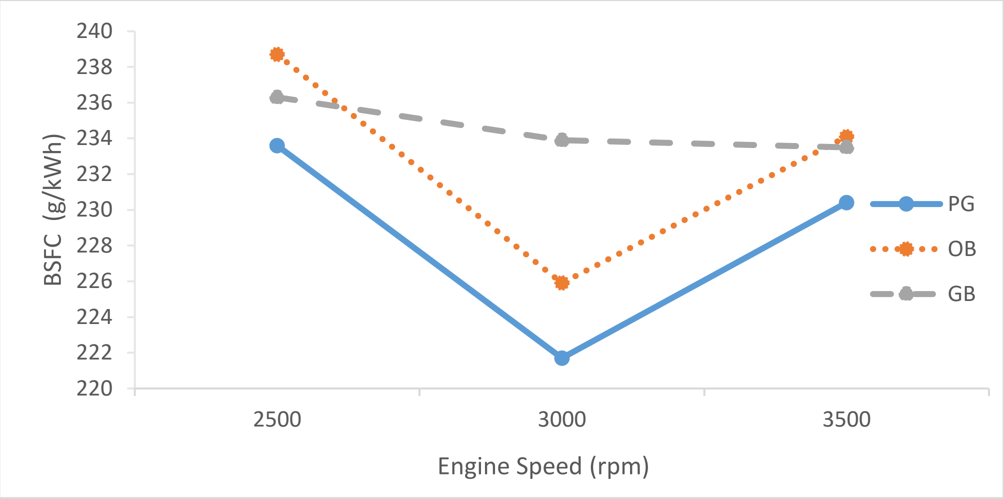

Figure 1: Effect of engine speed on BSFC for different blend ratios

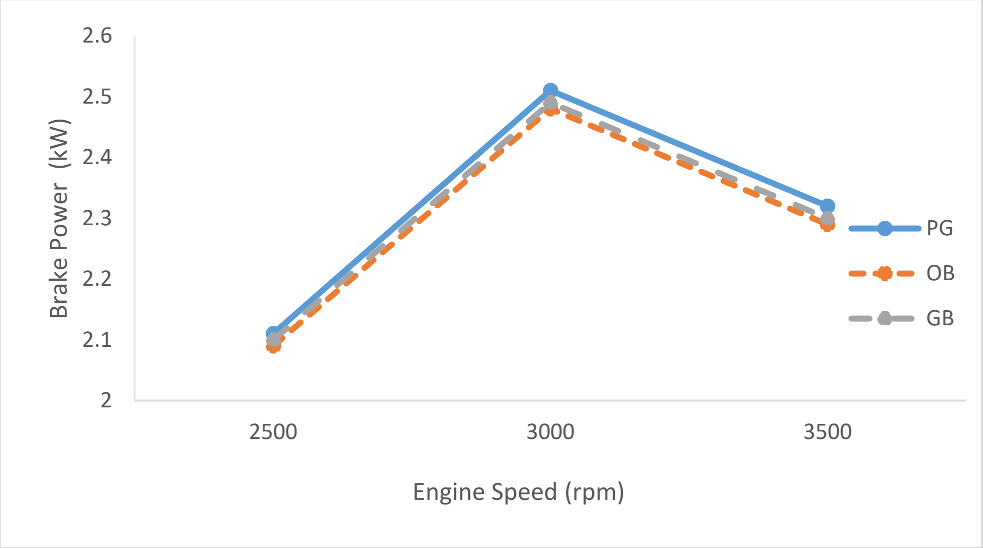

Figure 2: Effect of engine speed on BP for different blend ratios

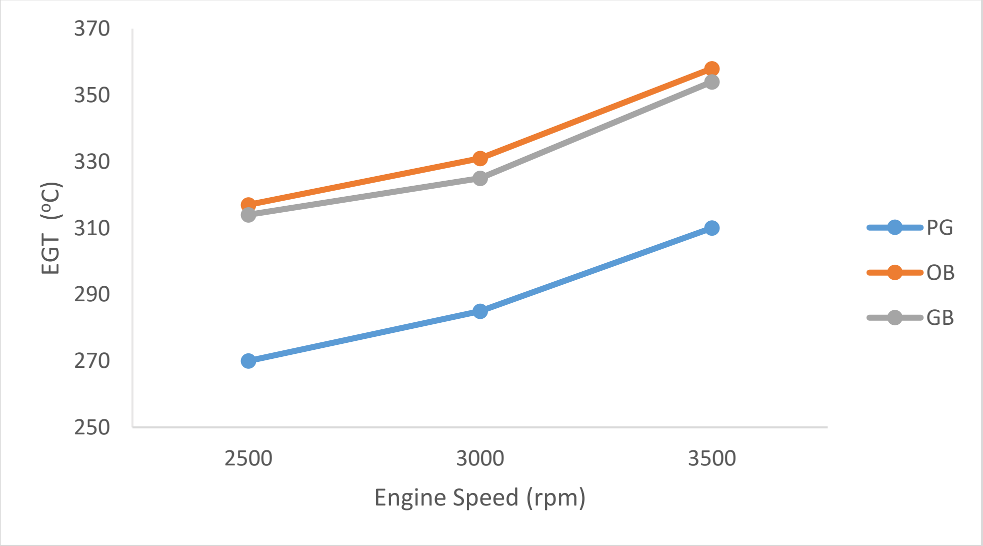

Figure 3: Effect of engine speed on EGT for different blend ratios

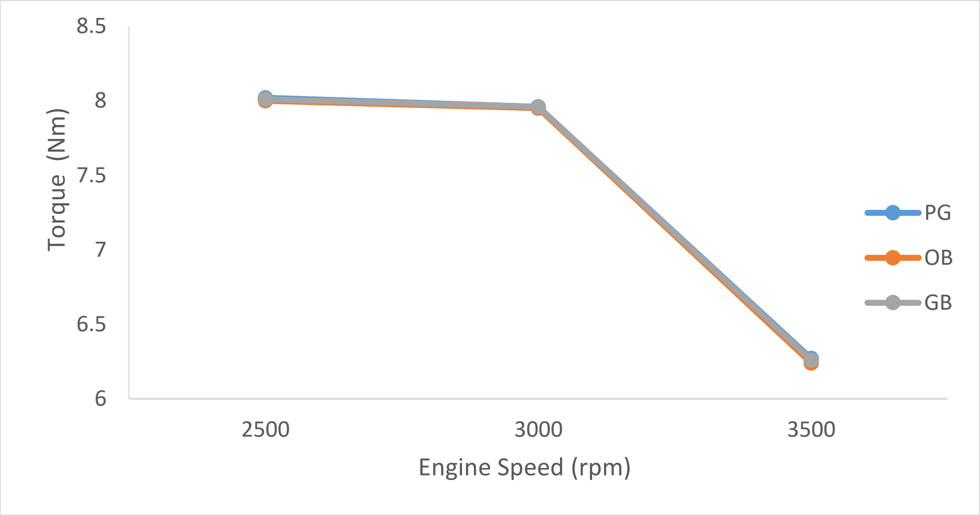

Figure 4: Effect of engine speed on torque for different blend ratios

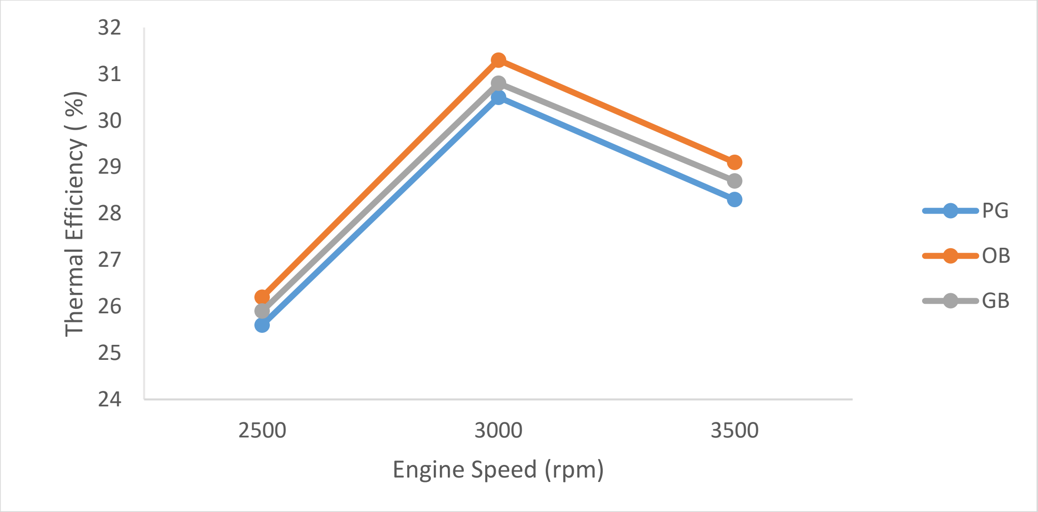

Figure 5: Effect of engine speed on thermal efficiency for different blend ratios

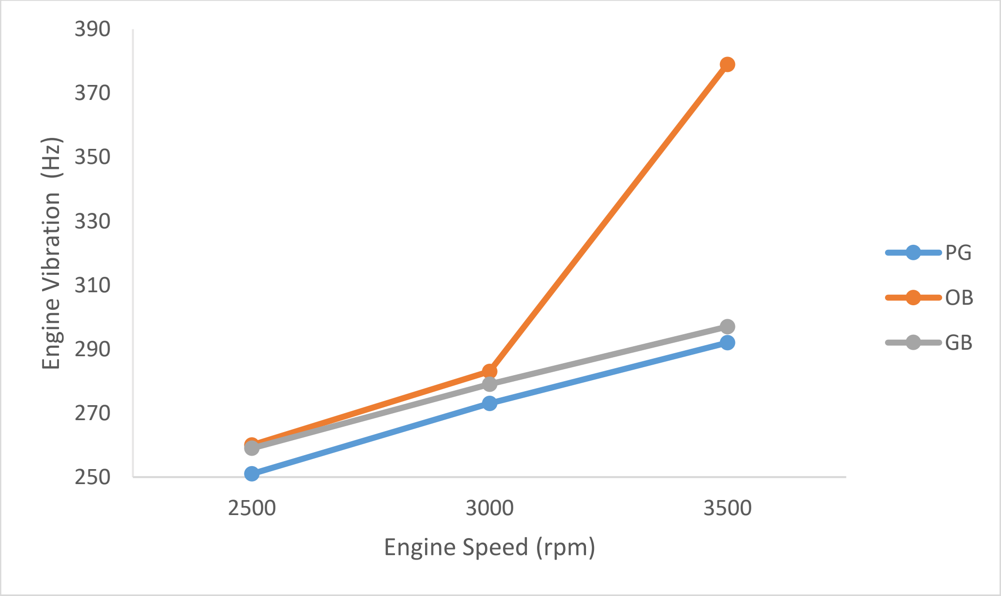

Figure 6: Effect of engine speed on engine vibration for different blend ratios

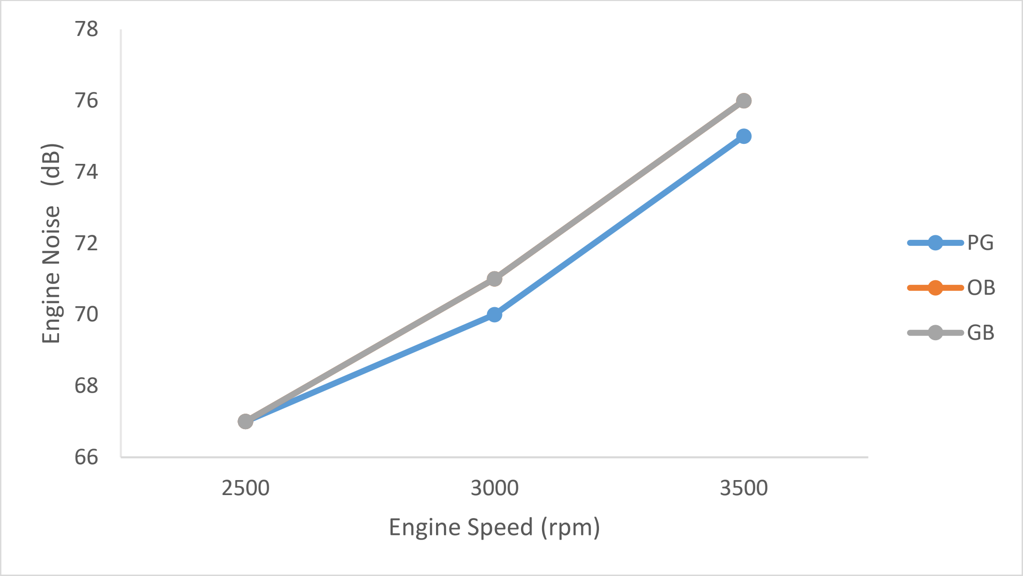

Figure 7: Effect of engine speed on engine noise for different blend ratios

CONCLUSIONS

The performance of Direct Injection Spark Ignition (DISI) engines fuelled with alcohol-gasoline blends has been evaluated. This study has demonstrated the potential of alcohol-based fuels to improve engine efficiency, reduce fuel consumption, and enhance power output. Models to predict the performance parameters of alcohol-gasoline blends were developed. The model summary statistics and ANOVA showed that all the models and model terms are significant, indicating their suitability to navigate the design space.

There was a marginal difference in the performance parameters obtained from a DISI engine fueled with pure gasoline and alcohol-gasoline blends. There was a 1.89% increase in BSFC for the optimum blend compared with pure gasoline while the thermal efficiency of the optimum blend was higher than that of pure gasoline by 0.9%. The optimum values of several performance parameters were obtained at 3000 rpm.

REFERENCES

Akbiyik T, Kahiaman N, and Tanep T. (2023). Energy and Exergy Analysis with Emissions Evaluation of a Gasoline Engine using different fuels. Fuel 345, 345-364

Ahmed E; Usman M; Anwar S; Ahmad H. M; Nasir M.W. and Malik M.A. (2021). Application of ANN to Predict Performance and Emissions of SI Engine Using Gasoline-Methanol Blends. Science Progress 104(1), 1 – 27.

Biswal A., Kale R., Teja G.R., Baneejee S., Kolhe P and Balusanly S. (2020). An Experimental and Kinetic Modeling Study of Gasoline/Lemon Peel Oil Blends for PFI Engine. *Fuel* **267**, 367-378

Costa J; Martins J; Arantes T; Goncalves M; Durao L; and Brito F. P. (2021). Experimental Assessment of the Performance and Emissions of a Spark-Ignition Engine Using Waste-Derived Biofuels as Additives. Energies 14(16), 106 – 114.

Elshenawy, M. A., Abou El-Maaty, M. A., El-Gohary, M. H., and El-Sayed, M. A. (2023). Recent Advances in Fuel Blends for Internal Combustion Engines: A Review of

Performance, Emissions, and Future Directions. *Energy Reports* 9, 252-275.

Heywood J.B. (2018). Internal Combustion Engine Fundamentals (2nd edition) MC Grow-Hill education, New York. 1- 999.

Iliev, I., Borojevic, D., and Jovanovic, M. (2021). Performance and Emissions of Internal Combustion Engines Fueled by Alternative Fuels: A Review. *Energy Reports* 7, 332-354

Jiahong F; Ruomiao Y; Xin L; Xiaoxia S; Yong L; Zhentao L; Yu Z. and Bengt S. (2022). Application of Artificial Neural Network to Forecast Engine Performance and Emissions of a Spark Ignition Engine. Applied Thermal Engineering 201, 411 – 424.

Karagoz Y; Balci O; Gezer O; Koten H; and Isin O. (2021). Performance and Emissions of Spark– Ignition Engines Fuelled with Petrol and Methane. Proceeding of the Institution of Civil Engineers – Energy 174(4), 156 – 169.

Liu, H., Wang, Z., Huang, Y., and Zhang, Y. (2018). A review of the effects of alcohol-gasoline blends on internal combustion engines. *Renewable and Sustainable Energy Reviews* 82, 356-372.

Lius, Lin Z, Zhang H, Fan Q, Lei N, and Wang Z (2023). Experimental Study on Combustion and Emission Characteristics of Ethanol-Gasoline Blends in a High Compression Ratio SI Engine. Energy 274 (6), 485-501.

Siwale R. F. and Bereczky P. M. (2018). Numerical Accuracy of the Kiva4 Code under Different Ignition Timing on the Combustion Characteristics of Gasoline in a Spark Ignition Engine. *Journal of Power and Energy Engineering* 6 (11), 354-367.

Zhang Y; Wang Q; Chen X; Yan Y; Yang R; Lie Z. and Fu J. (2022). The Prediction of Spark – Ignition Engine Performance and Emissions Based on the SVR Algorithm Processes 10, 201 – 221.

Zhou, L., Zhang, C., Huang, Z., and Wang, X. (2016). Performance and emissions of a direct injection spark-ignition engine fuelled with methanol/gasoline blends. *Energy Conversion and Management* 111, 216-223.

Zutta E; Acosta D; Duque A; and Diaz A. (2020). Development of Simulation Meta Models to Predict the Performance and Exhaust Emission Parameters of a Spark Ignition Engine. International Journal on Interactive Design and Manufacturing 14, 189 – 200.