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Research Paper

Design of Experiment to Predict the Effects of Graphene Nanoplatelets Addition to Diesel Engine Performance

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Abstract

To minimise diesel exhaust emissions, a few methods are commonly used. Engine modifications, combustion optimisation, and exhaust system treatment components are among them. Fuel additives, such as zinc oxide, titanium oxide, aluminium oxide, and cerium oxide, are amongst the most effective methods to increase performance and reduce emissions. Even while positive performance and emission reduction outcomes have been demonstrated, there are worries concerning health toxicity effects. Carbon nanoparticles have been accepted as a fuel additive since they pose little risk to human health. A few studies have been undertaken to investigate the consequences of employing graphene nanoplatelets as fuel additives, thanks to advancements in graphene research. The findings of the study seemed encouraging. However, despite detecting the additive effects of graphene on performance, no more study has been undertaken to forecast the effects on engine performance. The objective of this study was to predict the effects of graphene nanoplatelets as an additive for diesel engines. The performance parameters of the trial were torque, power, BSFC, and BTE. Speed, load, and blend concentration are all considered in this model. Response surface methods and contour plotting with Minitab software were used to generate the prediction model. The results show that the prediction model is within 10% of the experimental data.

Keywords: Graphene nanoplatelets; Response surface methodology; Contour plot; Engine performance; Engine emissions

1. Introduction

Greenhouse gas emissions have become one of the primary sources of global warming, which is a great challenge to the world today. The problem requires governments worldwide to put more restrictions on emission regulation which encourages the academic circle to look for sustainable solutions to energy supplies. Several techniques are regularly applied to reduce diesel exhaust emissions. These include engine modification, combustion refinement, and treatment components in the exhaust system.

Lately, various studies focusing on nanoparticles as additives to biodiesel fuels show that these additives have been significantly affecting combustion parameters [1], [2]. This effect is attributed to the nanoparticles' high surface area to volume ratio and high thermal conductivity [3], [4]. In recent years, there have been significant efforts focusing on the use of various metal oxide-based nanoparticle additives, such as zinc oxide, titanium dioxide, aluminium oxide, and cerium oxide, to improve the combustion behaviour of diesel and biodiesel and to reduce diesel engine emissions [5]–[7]. Despite the benefits mentioned earlier, metal-based nanoparticle additives and metal compounds emitted from combustion by-products are toxic and harmful to the environment [8]–[10]. For instance, some studies have concluded that metal oxide nanoparticles can cause different health problems, such as breathing, lung-related, and skin allergies [11].

Because metal-based fuel additives are toxic, researchers developed non-metallic fuel additives. Most additives are carbon-based nanomaterials like nano-biochar, graphite oxide, and carbon nanotubes (CNT). Researchers have taken steps to learn more about the effects of these materials as diesel additives. For example, Safieddin Ardebili [10] studied the impact of adding nano biochar to a diesel-fuel blend on performance and emissions. Heydari-Maleney [12] investigated the use of CNT as an additive in diesohol-B2 mixtures with the same goals.

Graphene, another carbon isotope, is another exciting material to be considered as a fuel additive. Since the discovery of the production method by Novoselov and Geim [13], graphene has been introduced in many applications such as biological engineering [14], ultrafiltration [15] and energy [16], [17]. Compared with other metal-based additives, graphene will not produce toxic emissions since the elements inside are just carbon [18]. Those studies found that the emission when the compressed ignition engine runs on the CNT-Diesel blend has improved. Not only did the emission improve, but the performance of the machine, such as engine torque, brake power, brake specific fuel consumption, brake mean effective pressure, and brake thermal efficiency, also improved [19]–[23].

Since graphene nanoplatelets (GNPs) are carbon-based and not metal-based, they can be an environmentally friendly fuel additive [24]. Due to its low toxicity, high energy density, and high thermal conductivity, it should be able to promote the combustion of diesel or biodiesel fuels [25]. Moreover, the advantageous characteristics of GNPs and the associated carbon nanomaterials have been proven in several other applications, such as in batteries, chemical sensors, heat transfer, and transparent conductors [26], [27].

A few researchers have performed experiments to understand the effects of adding GNP to diesel engine performance. The results were very positive as considerable improvements were found in BSFC and BTE. It is prevalent for researchers to extend the research with predictions on the effects of fuel with additives on the performance and emissions of the engine. Designs of Experiments (DOE) and the response surface methodology (RSM) are popular prediction methods applied by researchers [28] in engine performance studies. However, there is no prediction model available how the performance and emissions of the selected engine with a certain amount of GNP dosages in the diesel engine. Therefore, this research is intended to address those gaps by predicting the effects of GNP as a fuel additive to diesel engine performance using DOE and RSM.

2. Method

2.1. Graphene Nanoplatelets

The GNP are purchased from Sigma Aldrich. Samples of particles are subjected to Transmission Electron Microscopy (TEM) to study the shape and size of the material. The TEM pictures revealed that the particles are in the shape of platelets, as indicated by the manufacturer. This can be determined by observing the light colour of the forms, which suggests the presence of very thin sheets with a large surface area. The particles, in other words, have a significant diameter-to-thickness ratio. According to the manufacturer, the average thickness is 15 nm. A total of four graphene particles were measured. **Figure 1** shows the sizes measured from different directions.

The average diameter of the 32 measurements was 561.1 nm. This size is substantially smaller than the injector's 0.26 mm diameter (260000 nm). As a result, it has been confirmed to be nanoparticle sized and is not predicted to clog the injector. This is far less than the manufacturer's specified average diameter of 15 μm. The size difference is to be expected when GNP is manufactured in mass. This GNP observation is comparable to that of other studies [29]–[31].

2.2. Fuel Preparation

Pure diesel is used as the base fuel in this research. The fuel was purchased from fuel supplier Rahar Jati Sdn.Bhd. The GNP is then mixed with diesel by a mechanical stirrer at 800 rpm for 15 minutes, and directly afterwards, an Ultrasonication of 24 kHz for 30 minutes. The same method was applied by other researchers [18], [32]. According to literature, sonication can break apart GNP particles and avoid agglomeration [33]. In this test, the Hielscher UP400S was used.

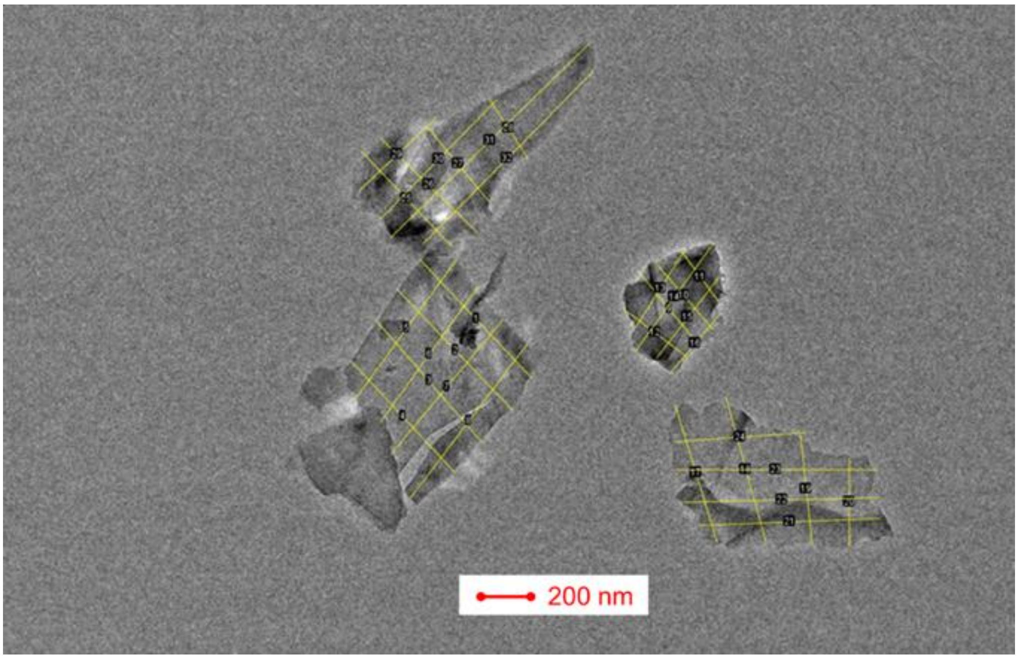

Figure 1. TEM image at 200 nm scale

Aside from pure diesel, four samples were blended with graphene. The quantity of the graphene was 25 ppm (D-GNP25), 50 ppm (D-GNP50), 75 ppm (D-GNP75) and 100 ppm (D-GNP100). The amount of graphene in the blends was also used in other literature [34], [35]. Properties of the diesel and fuel blends are as shown in Table 1.

2.3. Engine Setup and Test Cycle

The engine used in this experiment is a single-cylinder compression-ignition (CI) engine Yanmar TF120. It is a 4-stroke engine with a compression ratio of 17.7. The power output is rated at 12 hp, and the maximum speed is 2400 rpm. The experimental setup is shown in Figure 2.

In the beginning, the trial was run using pure diesel for a baseline measurement. The engine was run using diesel fuel at five different speeds (900 rpm, 1200 rpm, 1500 rpm, 1800 rpm, and 2100 rpm). By using a dynamometer, six different loads were applied (0%, 20%, 40%, 60%, 80%, and 100%). The run for each setting was repeated three times. The data from computers were downloaded for

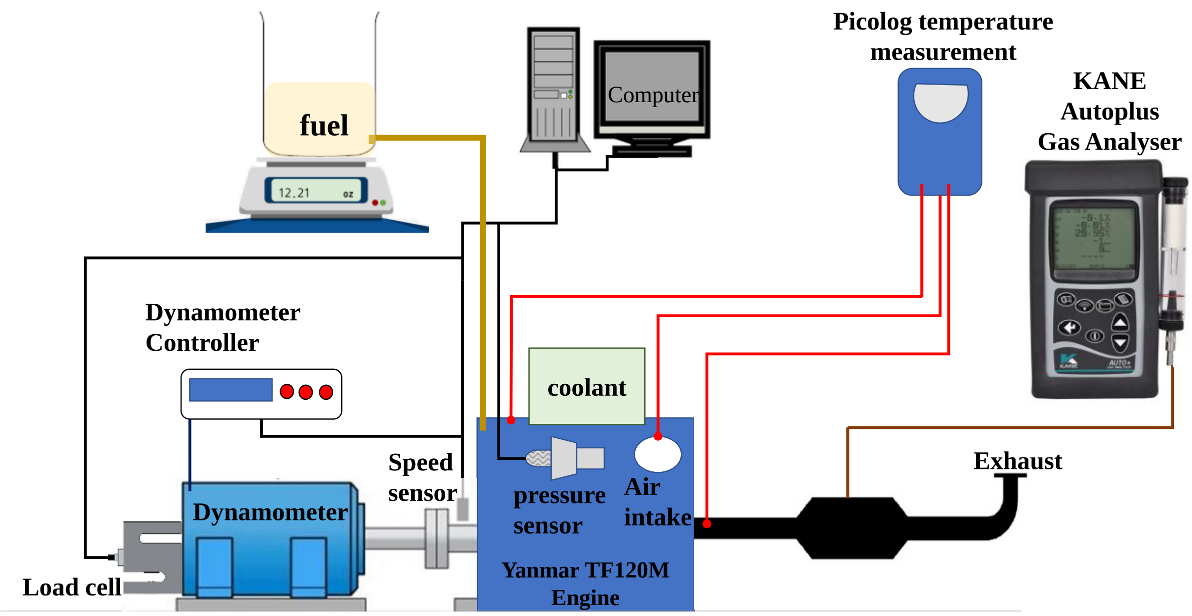

Figure 2. The experimental setup

Table 1. Properties of diesel and D-GNP blends

Properties	Diesel	D-GNP25	D-GNP50	D-GNP75	D-GNP100
Density (g/cm3)	0.8249	0.8251	0.8254	0.8251	0.8252
Kinematic viscosity (mm^2/s)	3.21	3.223	3.236	3.212	3.224
Dynamic viscosity (mPa.s)	2.6478	2.6595	2.6708	2.6506	2.6603
Calorific value (J/g)	44498	42856	43383	40337	43181

analysis. In analysing the performance, four indicators were used. The indicators used were brake torque, brake power, brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). The same experiment was then repeated with all the D-GNP blends.

2.4. *Prediction Method*

The prediction was performed using the MINITAB software. A step-by-step process is needed to perform the prediction. Firstly, a design of experiments (DOE) had to be set up. The DOE was created using a full factorial design. The three factors input were speed (rpm), load (%), and blend (ppm). Speed had five levels (900, 1200, 1500, 1800, and 2100) rpm, while load had six levels (0, 20, 40, 60, 80, 100) %. Five blend levels (ppm) were divided by five ppm concentrations (0, 25, 50, 75, and 100). From this input, MINITAB generated a table to fill in.

After running the experiments, the results were filled into the table generated by the software. A full quadratic term was applied. The terms included were speed, load, blend, speed*speed, load*load, blend*blend, speed*load, speed*blend, and load*blend. With this input, the software generated an equation that can predict the performance output based on the factors set up.

Furthermore, the response surface was chosen, and the surface plot condition was defined. The response is the parameter to predict our performance parameters (brake torque, brake power, BSFC, and BTE). Blend (ppm), speed (rpm), and load (%) were put in as factors in the X-Axis and Y-Axis. To present the RSM, a certain speed was chosen.

The analysis will be directed towards the most optimal engine run before moving on to a more in-depth analysis. As a result, a torque-power plot was created in a chart. The torque and power curves intersect at 1800 rpm, as shown in **Figure 3**. In general, this intersection indicates the optimum engine speed. As a result, the rest of the analysis will concentrate on the performance at 1800 rpm. The trends at different speeds are also very similar. Therefore, presenting the effects at 1800 rpm is enough. Next, the same method was applied step-by-step by choosing a contour plot.

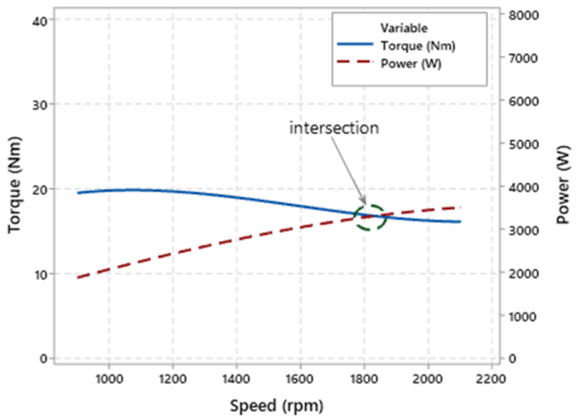

Figure 3. The intersection of torque and power curve at load of 60%

3. Prediction of Effects on Performance

3.1. *Brake Torque*

After preparing a full factorial DOE table, the data acquired from the experiments were input into the table. The experiments required the software to predict the torque in response to the three factors (speed, load, and GNP blend). The regression equation suggested for the torque is as Eq. (1).

A surface and contour plots were created to simulate the relationship between the torque and the factors in consideration, as shown in **Figure 4**. At 1800 rpm, it is clearly seen that the difference in load influences the change of torque value. However, the GNP concentration offers just a marginal effect on the torque. This is in line with research by El-Seesy [36]. With 0 ppm GNP, at 0% load, the torque is less than 5 N.m. At 100% load, the torque is more than 30 N.m. With the addition of 100 ppm GNP at 0% load, the torque is less than 5 Nm. At 100 % load, the torque produced is also more than 30 Nm.

$$\text{Torque (Nm)} = 1.40 + 0.00537\,S + 0.1629\,L - 0.0077\,B - 0.000002\,S{*}S + 0.002014\,L{*}L + 0.000014\,B{*}B - 0.000038\,S{*}L + 0.000003\,S{*}B - 0.000072\,L{*}B \quad (1)$$

Where: S is the speed in rpm; L is the load in %; B is the GNP blends in ppm

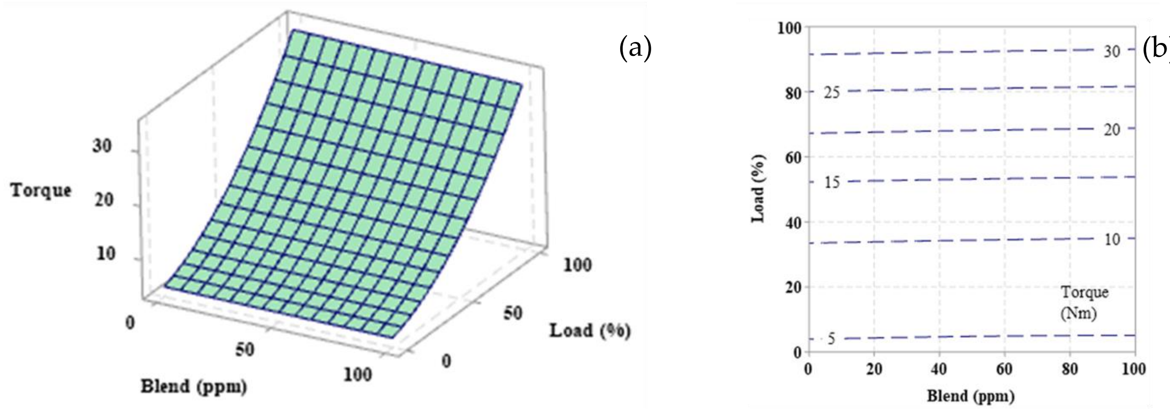

Figure 4. Torque prediction in the form of a) surface plot b) contour plot at 1800 rpm

From the charts displayed, it is concluded that GNP addition increased the engine's torque, especially at higher loads (80%–100%). This increase in torque after graphene addition is also observed by Heidari-Maleni [37]. However, it is effective only at higher loads due to the higher viscosity of the D-GNP blends. Higher viscosity causes difficulty in fuel atomisation, as mentioned in Section 2.1. However, a higher combustion temperature can fully atomise the D-GNP blends at a higher load, which means a higher quantity of diesel and GNP combusted. Therefore, higher torque of D-GNP blends is achieved at higher loads.

3.2. *Brake Power*

After preparing a full factorial DOE table, the data acquired from the experiments were input into the table. The experiments required the software to predict the power in response to the three different factors (speed, load, and GNP blend). The regression equation suggested for power is as follows Eq. (2).

For the surface plot of power vs blend, the load was plotted at 1800 rpm. A contour plot of those five speeds was also plotted to get a better reading of the model. The results are shown in **Figure 4**.

At speed 1800 rpm as shown in **Figure 5**, with the blend of 0 ppm and load 0%, the power produced is estimated at less than 1000 W. At load 100%, the power to be produced is estimated to be more than 6000 W. Similarly, with D-GNP100 at load 0%, the power to be produced is less than 1000 W, and at load 100%, the power will be more than 6000 W. It is clear the parameter load has more influence on the power output. Meanwhile, the power difference of GNP blends is not much to be seen.

Like the torque observation in section 3.1, the power of the D-GNP blends is lower than diesel at lower loads because of the poorer combustion of the fuel blends. This phenomenon happens since the higher viscosity of the D-GNP blends causes difficulty in fuel atomisation. However, a higher combustion temperature can fully atomise the D-GNP blends at a higher load, which means a higher quantity of diesel and GNP combusted. Therefore, higher power of the D-GNP blends is achieved at higher loads.

3.3. *Brake Specific Fuel Consumption*

After preparing a full factorial DOE table, the data acquired from the experiments are input into the table. The software was then required to predict the BSFC in response to the three different factors (speed, load, and GNP blend) in the experiments. The regression equation suggested for BSFC is as follows Eq. (3).

$$\text{Power (W)} = -649 + 1.811\,S - 21.46\,L + 0.35\,B - 0.000557\,S{*}S + 0.3230\,L{*}L - 0.0013\,B{*}B + 0.02457\,S{*}L - 0.00028\,S{*}B - 0.0122\,L{*}B \quad (2)$$

Where: S is the speed in rpm; L is the load in %; B is the GNP blends in ppm

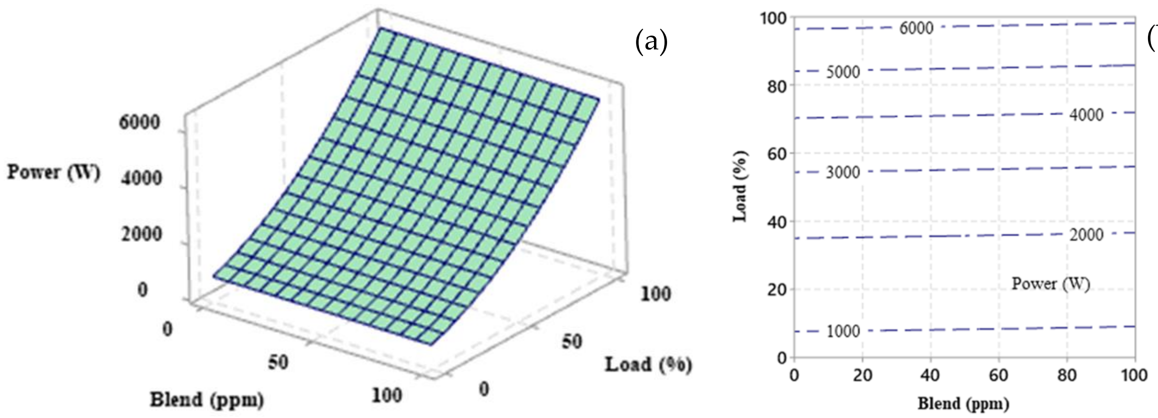

Figure 5. Power prediction in the form of a) surface plot b) contour plot at 1800 rpm

In general, the BSFC is lower at a higher load compared to a lower load. At speed 1800 rpm as shown in **Figure 6**, 0 ppm GNP and 0% Load, the BSFC is around 400 – 425 g/kW.h. When the load is raised to 60 – 85 %, the BSFC is about 325 – 350 g/kW.h. When the load is increased to 100%, the BSFC has increased again to 350 – 375 g/kW.h. The reason for this finding is that at a lower load, the D-GNP blends are difficult to atomise. The reason for that is the higher viscosity of the D-GNP blends compared to pure diesel. The addition of GNP increased the difference in BSFC at different loads. The contour is steeper with eight different steps at 100 ppm GNP as compared to 4 steps at 0 ppm GNP. With 100 ppm GNP at 0% load, the BSFC is more than 450 g/kW.h. With 100 ppm GNP at 100% load, the BSFC is less than 300 g/kW.h. At a high load, the combustion temperature becomes higher and therefore helps to atomise the GNP blended fuel better. The relationship of viscosity and fuel atomisation has been discussed by Du which mentioned that lower viscosity would improve fuel atomisation [38]. That is the reason for higher BSFC achieved at 100% load.

3.4. *Brake Thermal Efficiency*

The result of BTE from the experiment was put into Minitab with the result from the experiment. The regression model equation as suggested by the Minitab software is follows Eq. (4).

At speed 1800 rpm as shown in **Figure 7**, the difference in loads has more influence on the BTE. It is observed there is a big difference in the BTE when load 0% is compared to the BTE at load 100%. This is true for all blends. However, note that when GNP is added to the blend, the range of the BTE gets bigger. For example, at load 0% and 0 ppm GNP, the BTE is around 18 – 20%, and at 100% load, the BTE is around 22% - 24%. When 100 ppm of GNP is added, at 0% load, the BTE is

$$\text{BSFC (g/kW.h)} = 394.1 - 0.1352\,S - 1.351\,L + 1.511\,B + 0.000071\,S*S + 0.01392\,L*L - 0.00078\,B*B - 0.000326\,S*L - 0.000459\,S*B - 0.01081\,L*B \quad (3)$$

Where: S is the speed in rpm; L is the load in %; B is the GNP blends in ppm

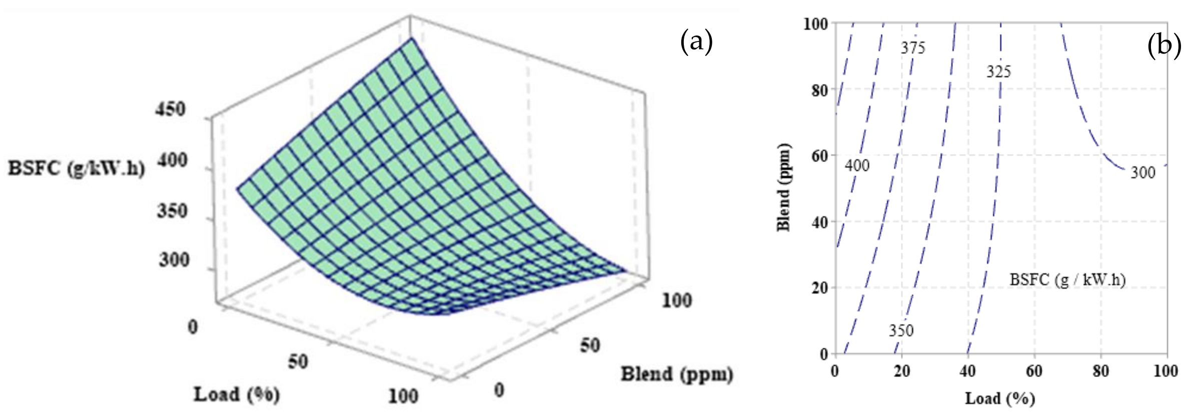

Figure 6. BSFC prediction in the form of a) surface plot b) contour plot at 1800 rpm

less than 18%, and at 100% load, the BTE is more than 26%. This observation is that at a lower load, energy from GNP is not fully utilised, but graphene's weight is considered in the calculation. At higher load, however, the amounts of GNP combusted have increased due to higher temperature. In other ideas, according to El-Seesy, the higher thermal conductivity of GNP helped to improve the evaporation rate of fuel droplets, subsequently improving BTE [36].

3.5. Comparison Between Performance Experimental Value and Model Value

To compare the experimental data against the modelled value, the value of variables which are speed, load, and blend concentration, were put into the equations of torque, power, BSFC, and BTE. Bar charts were created using the experimental values and the calculated values. The value of experimental data and model data are represented side by side, as shown in **Figure 8**.

The green bars represent the experimental values, while the red bars represent the model values. From the observation, the experimental and model values agree with each other, where the difference is only less than ±10%. This acceptance level is also shared by other researchers [39], [40]. This is true for all the performance indicators selected (brake torque, brake power, BSFC, and BTE).

$$\text{BTE (\%)} = 16.77 + 0.01421\ S + 0.0999\ L - 0.0451\ B - 0.000006\ S{*}S - 0.000770\ L{*}L - 0.000208\ B{*}B + 0.000010\ S{*}L + 0.000026\ S{*}B + 0.000616\ L{*}B \quad (4)$$

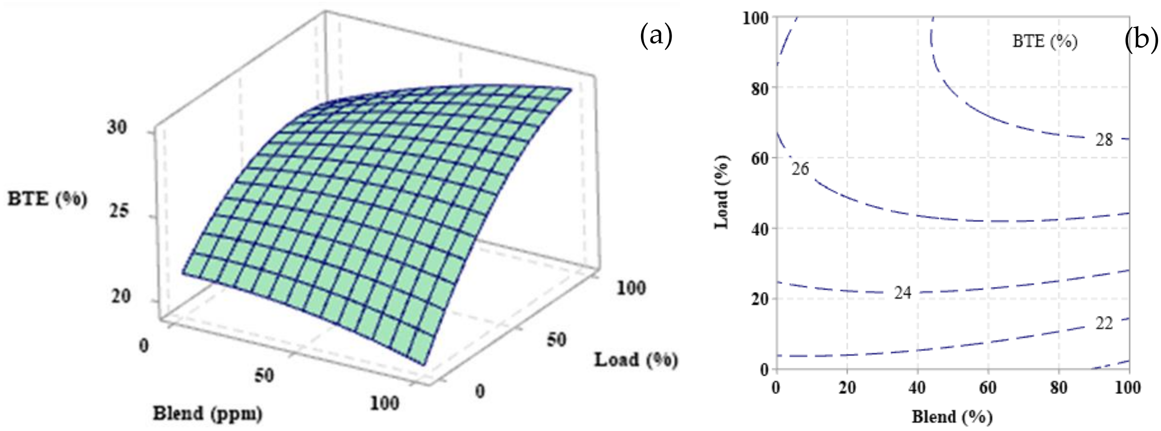

Figure 7. BTE prediction in the form of a) surface plot b) contour plot at 1800 rpm

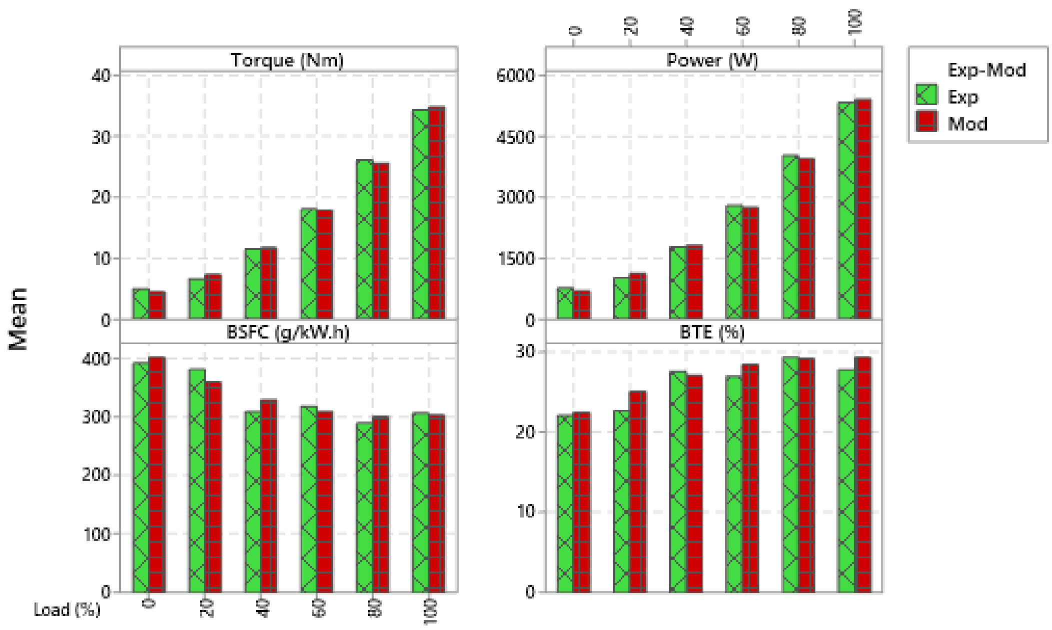

Figure 8. Performance comparison of experimental value against model value

4. Conclusion

This study has tried the effects of the D-GNP blends usage as an additive in a compression-ignition engine. By using the response surface methodology and contour plot, the prediction of performance was conducted. The prediction model of all the performance parameters (Torque, Power, BSFC, and BTE) showed good agreement with the experimental data (less than ±10%). In order to get a deeper understanding in the future, multi-objective optimisation may be applied because what is optimal for one response may not be optimal for other responses. For example, optimal parameters for BSFC is not optimal for CO emissions and vice versa.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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