

Research Paper

Effect of Graphene Oxide Addition on Spark Ignition Engine Performance and Cycle-to-cycle Variation with Gasoline-ethanol Fuel

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Abstract

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A fuel blend of gasoline and ethanol increases octane, meets air quality standards, and satisfies renewable fuel mandates, but the blend does not always result in perfect bonding, causing fuel separation and increasing cyclic variation. To overcome these limitations, up to 60 ppm graphene oxide (GO) nanoparticles were added into an 80:20 gasoline-ethanol blend (E20) and tested for the first time on a spark-ignition (SI) engine. The engine performance was evaluated by measuring cyclic variation, combustion stability and pressure, torque and power, specific fuel consumption, and CO₂ emission. The acquired data were then statistically treated by using a coefficient of variation (COV) and then evaluated with Response Surface Methodology (RSM) in order to demonstrate a strong ability to accurately predict the optimization. Results show that the addition of GO nanoparticles into the E20 reduced the COV by up to 19.54% at an engine speed of 8000 rpm when compared to E20 alone, while the torque and power both increased by 5% at 5500 rpm. The specific fuel consumption of the GO-E20 blend was up to 15% higher than that of E20, with a decrease in CO emission but an increase in CO₂ emission. Generally, the E20GO blend positively impacts the SI engine's cyclic stability and performance, but its potential adverse effects on the environment and health must be carefully considered.

Keywords: Graphene Oxide; Ethanol; Spark-ignition engine; Performance; Cycle-to-cycle variations

1. Introduction

The annual increase in the number of vehicles is directly proportional to the use of fuel and the increase in exhaust emissions. However, the driving behavior also significantly influences this trend [1]. Increasing fuel use in internal combustion engines (ICEs) contributes to CO₂ air pollution in the environment, which is a major environmental concern [2]. Fossil fuel-powered vehicles are among the primary sources of air pollution, and the growing reliance on passenger cars further elevates per capita carbon production.

As most people still use private vehicles, the cumulative carbon output continues to rise, degrading air quality and posing substantial public health risks.

The rise carbon emissions are driven by growing fossil fuel consumption, which simultaneously supports regional economic development [3]. Consequently, solutions are required to reduce reliance on fossil fuel resources. One promising approach involves the gradual adoption of alternative fuels [4]. Extensive research has explored to find alternatives to fossil fuels, particularly alcohol-



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Abreviation	
ANOVA	: Analysis of Variance
BTDC	: Before Top Death Center
°CA	: Crank Angle Degree
°CA at P_{max}	: Crank Angle Degree at the P _{max}
COV	: Coefficient of Variance
COV_{Pmax}	: Coefficient of Variance of Peak Pressure
COV_{IMEP}	: Coefficient of Variance of IMEP
CO	: Carbon Monoxide
CO₂	: Carbon Dioxide
E20	: Gasoline 80% + Ethanol 20%
E20GO	: E20 + 60ppm GO
GO	: Graphene Oxide
HRR	: Heat Release Rate
IMEP	: Indicative Mean Effective Pressure
NO_x	: Nitrogen Oxide
P_{max}	: Peak Pressure
RPM	: Rotation per Minuet
RSM	: Response Surface Method
SFC	: Specific Fuel Consumption
THR	: Total Heat Release

based fuels such as ethanol. However, the use of ethanol in spark-ignition (SI) engines imperative to modifications, such as adjustments the compression ratio and ignition timing depend on the combustion duration and injector spray dynamics. These optimizations are critical for achieving peak efficiency and minimizing emissions, given ethanol's high-octane properties [5]. Additionally, biofuels offer significant emissions reduction potential, because biofuels are considered greater sustainability in life cycle assessments compared to conventional fuels [6].

Ethanol possesses a higher octane-number (108–109) than conventional gasoline (typically 90–98), enabling it to tolerate higher compression ratios without knocking. Additionally, ethanol's faster flame speed promotes more complete combustion before exhaust valve opening, resulting in a higher total heat release compared to gasoline [7]. However, ethanol's lower heating value leads to increased fuel consumption relative to gasoline, despite its more efficient combustion conversion. Blending ethanol with gasoline presents several challenges, such as separation between the two fuels [8], corrosion [9], [10], [11], vapor lock, and combustion cycle instability [12], [13]. But in modern gasoline engines, a 20% ethanol blend (E20) can be used as a fuel without the need for engine modifications and without compromising performance [14]. A major issue is phase separation, which occurs when the blended fuel is stored for an extended time. It is assumed that unused in the vehicle's tank, the ethanol-gasoline mixture can separate, leading to inconsistent fuel composition entering the combustion chamber. This instability results in degraded combustion performance, which is also referred to as cycle-to-cycle variation (CCV). The coefficient of variation (COV), calculated as the ratio of the standard deviation of peak cylinder

pressures to their mean value across multiple cycles, is a widely used metric for assessing CCV [15].

Several approaches have been proposed to mitigate COV. From a mechanical standpoint, dual-injector systems—where each fuel (e.g., gasoline and ethanol) is delivered via a dedicated injector—have demonstrated potential [16], [17]. Alternative approaches involve fuel additives, including methanol [18], [19], ethyl acetate [20], and oxygenated compound [15], [21], [22]. To advance understanding of COV dynamics, this study investigates the COV of gasoline-ethanol blends enhanced with graphene oxide (GO) nanoparticles. Owing to their van der Waals interactions, GO nanoparticles exhibit dual functionality: they facilitate homogeneous dispersion of gasoline and form stable bonds with ethanol, thereby theoretically suppressing phase separation and reducing COV. In addition, the presence of oxygen functional groups facilitates a more uniform oxidation process within the fuel [23]. The high surface area and thermal conductivity of GO, compared to other fuel components, are key advantages that contribute to enhanced combustion [24].

GO has demonstrated positive effects in compressed ignition (CI) engines. As a nano-additive, GO improves engine performance through its catalytic activity and oxygen content which improve combustion characteristics [25]. Key benefits include reduced ignition delay [26], increasing thermal efficiency [27], [28] and increasing power and torque output [29]. These improvements arise from GO's high specific surface area, which promotes fuel adheres and accelerates vaporization. Furthermore, GO lowers the activation energy required for combustion, leading to faster ignition and shorter ignition delays [30]. The addition of GO to biodiesel, GO

significantly reduces NOX emission compared to using pure biodiesel fuel [31]. Beyond fuel applications, graphene nanoparticles have also been utilized in engine lubrication systems to improve oil performance [32]. Selected recent studies are summarized and compared in Table 1.

Given the demonstrated advantages of GO, the primary objective of this study had to quantify the COV in a gasoline-ethanol fuel mixture enhanced with GO nanoparticles. The second to evaluate the effects of this nano-additive on engine performance, fuel consumption, and emissions characteristics. These investigations provide critical insights into the practical implications of GO utilization in ethanol-gasoline fuel formulations, advancing the understanding of its potential for optimizing combustion stability and environmental performance.

2. Methods

2.1. Experimental Setup

The study was carried out in a lab at the National Research and Innovation Agency's Thermodynamic Motor and Propulsion Laboratory (Figure 1). The test engine was positioned in the test cell, with a dynamometer recording power and torque data. A flowmeter in the fuel system measured fuel consumption, while thermocouple-based temperature sensors were also installed. An instrument module, linked to a control computer, managed throttle position and engine speed while also tracking oil temperature, exhaust temperature, and sensor data from the test cell. Key components of the setup included the test engine, dynamometer, and fuel system. The ECU (Electronic Control Unit) originally uses from engine and AFR meter (Air Fuel Ratio meter)

Table 1. Internal combustion engine fueled with nanoparticle recent study

Authors	Fuel	Nanomaterial	Key result
Chacko & Jayaseelan [29]	Biodiesel	Graphene Oxide & Graphene nanoplatelets	GO and GNP improved combustion characteristics by reducing ignition delay and premixed burn fraction. GO and GNP did not adversely impact the fuel filterability and injector wear characteristics. 40 ppm of GO and 60 ppm of GNP were found to be the optimum concentrations for improved performance and emissions.
Hoang [33]	Biodiesel	CeO ₂	Adding CeO ₂ nanoparticles to biodiesel blends enhances the combustion process, reducing heat release rate and in-cylinder pressure. Reducing CO, HC and smoke emissions from biodiesel-fueled engines.
Yaqoob <i>et al.</i> [34]	Petrol and pyrolysis oil	Fe ₂ O ₃ & graphite	Highest energy efficiency, Highest exergy efficiency, Best thermoeconomic performance, Maximum sustainability index, is implication after using Fe ₂ O ₃ nanoparticle into fuel
Mosadegh <i>et al.</i> [35]	ethanol	Graphene oxide	Ethanol droplets doped with rGO and pGO, the ignition delay increases almost linearly with increasing the loading concentration from 0.01 to 0.1%. ethanol droplets doped with hGO feature a maximum ignition delay at the doping concentration of 0.01%. For all tested conditions, a maximum increase of about 21% was observed in the ignition delay of ethanol doped with pGO, for the loading concentration of 0.1%.
Ma <i>et al.</i> [36]	Diesel-Methanol	graphene oxide, multilayer graphene, and carbon nanotubes	This resulted in increased peak cylinder pressure, peak heat release rate, and reduced ignition delay and combustion duration. Graphene oxide exhibited the best optimization effects among the three nanoparticles. The nano-fuels showed lower brake-specific fuel consumption and higher brake thermal efficiency under nearly all load conditions. Reduced emissions of CO, HC, and smoke opacity, while NO _x emissions slightly increased.

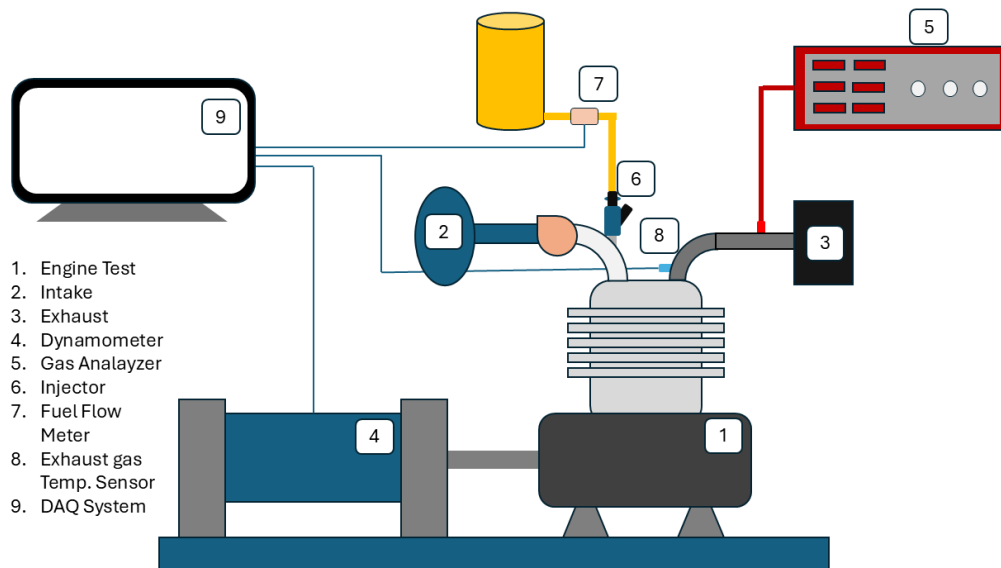


Figure 1. Experimental setup from basic motorcycle engine Honda, Supra JBN1E

was products of BRT, where the company is producing modification part for the race including EFI system (electronic fuel injection system). Then CO and CO₂ measurements were performed using a gas analyzer (Qirotech 401), and all instruments were calibrated according to the instructions. **Table 2** is lists the characteristics of the instruments used in this study.

The engine used in this study was an SI Honda engine of type JBN1E, a single-cylinder 125 cc SOHC with an electronically controlled injection system. The general specifications of the test engine are shown in **Table 3**. The data acquisition process was carried out under steady-state conditions, and the engine was conditioned with an oil temperature of 50-100 °C at a constant engine speed, while the throttle was 100% open with a full load according to the dynamometer. The data collection points were established between engine speeds of 4000 RPM and 8500 RPM in increments of 1000 RPM. This range of engine speeds is assumed to cover both medium and high operating ranges. Low engine speeds

were not considered because the centrifugal coupling system may need to operate optimally at lower engine speeds, potentially leading to inaccurate data collection.

2.2. Fuel and Graphene Oxide

The primary fuel in this research was RON 90 gasoline, sourced from PT Pertamina gas stations, with its detailed specifications provided in **Table 4**. Additionally, the ethanol used was supplied by Merck. **Table 5** shows the nano-additive GO specification. A GO concentration of 60 ppm was used in this study. The mass fractions of gasoline and ethanol in E20 were 80% and 20%, respectively. Here, it was assumed that the ethanol purity was 100%. The procedure for blending gasoline-ethanol with GO was initiated by diluting GO in ethanol, and the resulting mixture of gasoline and ethanol + GO is denoted as E20GO. Following the blending of the three components, the mixture was subjected to sonication for 150 minutes (5 × 30 min intervals) at 70 °C to fully disperse the GO nanoparticles.

Table 2. Specification of gas analyzer, pressure transducer, thermocouple and dynamometer

Instrument	Brand/Type	Range	Accuracy
CO	Qirotech 401	0-9.99(%)	0.01(%)
CO ₂	Qirotech 401	0-9.99(%)	0.1(%)
Pressure	KISTLER 6215	0-200 bar	1.5(%)
Flow meter	GPI	1-10 l/h	0,001(%)
Thermocouple	Type K	0-1200 °C	0.1 °C
Dynamometer	Bull	1-30 Nm	0.25 Nm

Table 3. Engine test specifications

Properties	Specification
Manufacture	Honda, Supra AFX12U21C07
Engine Type	Spark Ignition (SI), 4 Stroke, SOHC
Cooling Type	Air Cooling
Cylinder	Single
Bore	52.4 mm
Stroke	57.9 mm
Volume Cylinder	124.89 cc
Compression Ratio	9.3 : 1
Power Max	7.4 kW @ 8000 RPM
Torque Max	9.3 Nm @ 4000 RPM
Fuel system	Programmed fuel injection (PGM-FI)

Table 4. Specifications of gasoline and ethanol

Properties	Gasoline [22], [37]	Ethanol [22]
Density (kg/L)	0.729	0.793
AFR	14.7	8.9
LHV (MJ/Kg)	44	27
Oxygen content (Wt%)	1.01	35.7
Mol (g/mol)	95-120	46
Boiling Point (°C)	25-215	78.4
Vapour Pressure at 38 °C (kPa)	58.4	17.4
Autoignition (°C)	300-400	363

Table 5. Specification of graphene oxide [29]

Properties (Units)	Value
Number of layers (-)	1-3
Average thickness (nm)	1-4
Surface Area (m ² /g)	200
Thermal conductivity (W/mK)	8.87
Carbon (%)	77
Oxygen (%)	22
Other (%)	1

The Graphene Oxide is synthesized based on modified Hummer Method [38]. To obtain the GO that was used, 1 g solid of graphite was mixed with 0.5 g NaNO₃ and then dispersed in 46 mL H₂O₄ solution. The solution was stirred in an ice bath to prevent an explosion. Then, 3 g KMnO₄ was slowly added to prevent reactions due to temperatures higher than 20 °C, and the solution was stirred for 6 hours at 30 °C. After that, another 3 g KMnO₄ was added and held at the same temperature for 12 hours. The next stage involved the gradual addition of 6 mL of H₂O₂, and the temperature was maintained at no more than 80 °C. This addition was intended to reduce KMnO₄ and MnO₂ residues to Mn²⁺ and to dissolve them. At this stage, the color of the solution changed from dark brown to bright yellow. The next stage involved the separation of GO from the solution so that it could be used for various applications.

After the GO was stirred for 18 hours, it was washed with distilled water (pure H₂O) until it reached a neutral pH, indicating that the reaction had stopped. The acidic solution obtained during the synthesis was separated, after which the GO precipitate was dissolved in distilled water and filtered using a vacuum pump. Flow process based on the method can be seen [Figure 2](#).

2.3. Coefficient of Variation

Pressure measurements were conducted using a Kistler 6617B piezoelectric sensor, with data acquisition managed using LabVIEW software. Pressure readings were taken at 0.25 crank angle degree (°CA) intervals, accumulating 100 cycles. The obtained pressure data were processed using the COV. Pressure analysis began at the combustion start point at 15 °CA BTDC (Before Top Death Center) and continued until exhaust valve opening. The results were calculated and expressed as percentage values [37].

The COV measures how consistent an engine's combustion is from one cycle to another. It's calculated by comparing how much the pressure varies (standard deviation) to the average pressure. The peak pressure (P_{max}) and indicative mean effective pressure (IMEP) are crucial parameters for measuring cyclic variations. P_{max} is

measured at the point where the Otto cycle reaches its maximum pressure, whereas IMEP represents the average pressure measured throughout the entire cycle. Hence, the measured $COV_{P_{max}}$ is referred to measured P_{max} pressure, and COV_{IMEP} is referred to measured IMEP pressure. The COV (Coefficient of Variation) was calculated using Eq. (1), where the standard deviation of IMEP σ_{IMEP} is divided by the mean the mean IMEP value μ_{IMEP} . The IMEP is defined as the work done (W_c) divided by the engine's volume displacement (V_d) per cycle, as shown in Eq. (2).

$$COV = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100\% \quad (1)$$

$$IMEP = \frac{W_c}{V_d} \quad (2)$$

Response Surface Methodology (RSM) is generally used to model processes that have multiple influencing factors and develop predictive equations for determining the optimal value of a process parameter [39]. The RSM method is also used to optimize engine performance, particularly when using nano-additives in combustion [40]. Based on the data obtained, concentration GO, Engine Speed are factors, whereas $COV_{P_{max}}$, COV_{IMEP} , P_{max} , IMEP,

and $^{\circ}CA$ at P_{max} , serve as optimization responses. Using Response Surface method and Blank Spreadsheet design type, the data was used to develop an appropriate regression model with Design Expert software (version 13).

3. Results and Discussion

3.1. Graphene Oxide Characterization

The sample was also characterized by SEM and FTIR to confirm that oxidation was successful and GO was formed. The SEM image (Figure 3) shows a typical morphology of GO nanosheets synthesized through exfoliation methods such as the modified Hummers method. The micrograph reveals irregularly shaped, flake-like structures distributed over the substrate, with lateral dimensions ranging approximately from 1 to 10 μm . These sheet-like features are characteristic of GO and suggest successful exfoliation from bulk graphite. The variation in grayscale contrast across the flakes indicates differences in thickness, where darker regions likely represent multilayer GO, and lighter, more transparent flakes suggest monolayer or few-layer GO. The flakes appear well-dispersed with minimal aggregation, which implies effective dispersion during sample preparation.

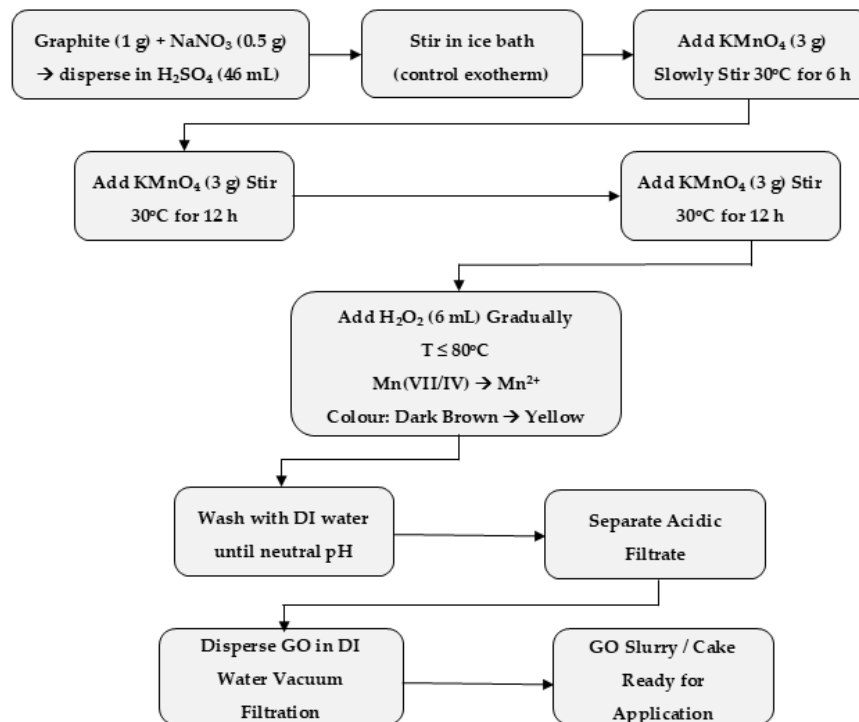


Figure 2. Flow process method for making GO

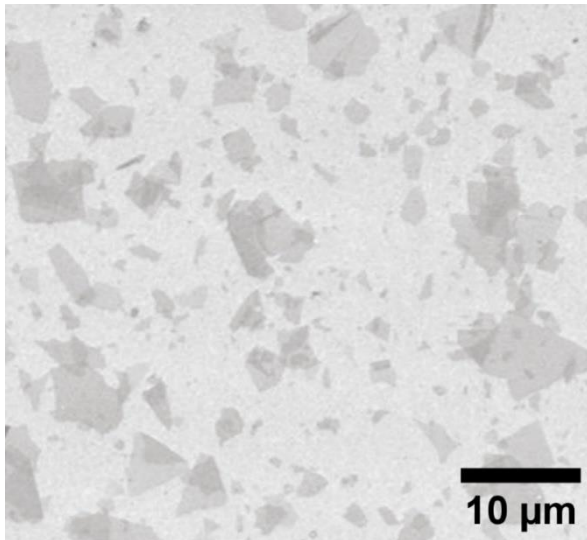


Figure 3. SEM image morphology of GO using modified Hummer method

The FTIR spectrum of the synthesized GO (**Figure 4**) shows several characteristic adsorption bands that confirm the presence of various oxygen-containing functional groups, indicating successful oxidation of graphite. A broad and intense adsorption band centered at 3159 cm^{-1} to the stretching vibration of hydroxyl ($-\text{OH}$) groups, which is a hallmark of GO due to the introduction of oxygen functionalities. A smaller peak around 2807 cm^{-1} is attributed to C–H stretching vibrations, likely from residual hydrocarbon moieties or edge defects. The sharp adsorption band at 1709 cm^{-1} is assigned to the C=O stretching vibration from carbonyl or carboxylic acid groups. Additionally, a peak at 1627 cm^{-1} is associated with the stretching of C=C bonds in aromatic domains, which are partially retained from the original graphite structure. The presence of epoxy or alkoxy groups is confirmed by the adsorption peak at 1196 cm^{-1} , corresponding to C–O stretching vibrations. Collectively, these spectral features are consistent with those reported in the literature for GO synthesized via chemical oxidation, such as the modified Hummers method. These functional groups are characteristic of graphene oxide and align well with values reported in the literature [41], [42], [43], [44].

3.2. Cycle to Cycle Variation

This experiment has a data plot of combustion pressure, which shows the pressure values every 0.25°CA , as an aggregate of the data from 96 cycles. The plot shows the difference between

each cycle, which represents the repetition of combustion [45]. **Figure 5** shows the peak pressures at an engine speed of 4000 RPM with E20 fuel. This figure can be observed from one cycle to another. These significant pressure variations caused performance to fluctuate, which can affect engine vibrations; however, further investigation is necessary to thoroughly examine this issue. To determine the cycle variation from the engine, we adopted the COV method, which is the most common method for studying combustion pressure variations. This approach involves determining the coefficient of variation for each Otto cycle.

In general, P_{max} has a wider scatter distribution than the IMEP. This suggests that P_{max} is more sensitive to cycle-to-cycle combustion, as illustrated in **Figure 6**. This is evident from the elongated scattering distribution. According to Hong *et al.* [46], $\text{COV}_{P_{\text{max}}}$ is a superior indicator of cyclic variation CA0-10 dan CA10-90, thus enabling the mapping of the unstable combustion process. In contrast, COV_{IMEP} elucidates the combined characteristics of engine performance, and the simultaneous utilization of both indicators is an effective approach to assess cyclic variation. **Figure 6** illustrates that the IMEP tends to decline as the engine speed increases, particularly between 7000 RPM to 8500 RPM. Close examination of **Figure 6** shows that the inclusion of ethanol in the fuel tends to result in a slight increase in the IMEP value. The addition of GO has been found to elevate the IMEP by a greater extent than that observed when using E20 fuel at an engine speed of 6000 RPM. However, at other engine speeds, no

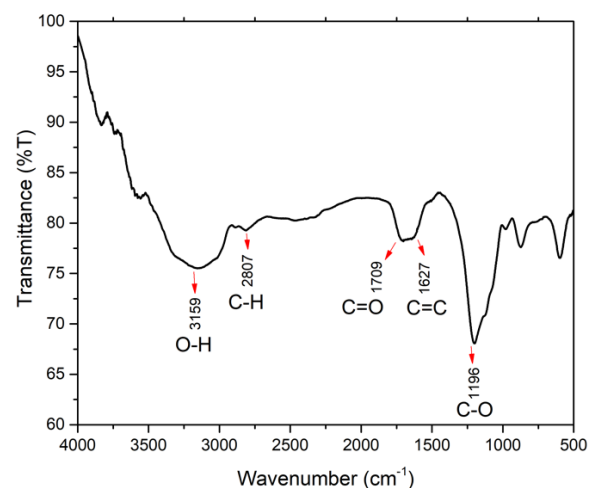


Figure 4. FTIR spectrum of the synthesized GO

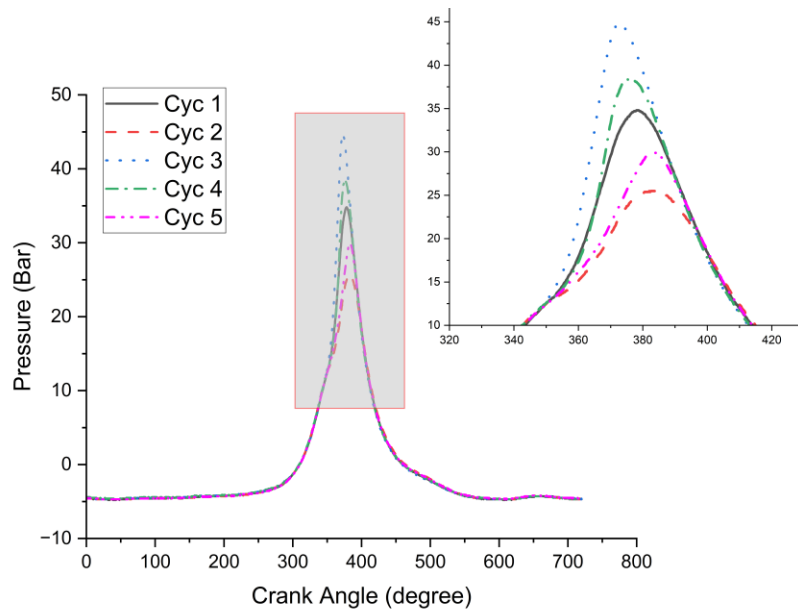


Figure 5. Cycle variation or differentiation cycle for SI engine with E20 fuel

notable alterations were observed. The distribution of P_{max} for all fuel samples and engine speeds yielded no significant results, indicating that all samples exhibited an even distribution.

With the addition of GO, the COV of the SI engine was reduced, as shown in [Figure 7](#) and [Figure 8](#). E20GO had a significant decrease in the $COV_{P_{max}}$ value with an engine speed of 8000 RPM, up to 19.54% compared with that of E20, and this reduction in the COV was significant at both high speeds. There was only a slight decrease in the middle engine speed from approximately 5000 RPM. At 8500 RPM, $COV_{P_{max}}$ increased marginally by 5% for the E20GO compared to E20. In [Figure 8a](#), COV_{IMEP} presented results similar to those of $COV_{P_{max}}$, but slightly different results at engine speeds of 4000 RPM and 5000 RPM. The lowest COV_{IMEP} value was obtained at 6000 RPM, which was a 22% decrease, but at an engine speed of 5000 RPM, the value of COV_{IMEP} increased by approximately 30%, as shown in [Figure 8a](#); the COV_{IMEP} value change was not significant.

GO shares common characteristics with other nano-sized materials; it possesses strong intermolecular binding forces, such as van der Waals forces, which enable it to bond with gasoline. Additionally, it exhibits electrolytic ion strength, which allows it to form agglomerates with ethanol [23]. An issue that has persisted in dual-fuel systems involving gasoline and ethanol is the occurrence of separation, which leads to

uneven combustion between cycles. Thus, GO can reduce the COV by binding gasoline molecules through intermolecular forces and capturing ethanol through its atomic bonds. It is assumed that the fuel entering the combustion chamber maintains a consistent concentration when bound to GO, without considering the fuel composition, which is not within the scope of this discussion. Therefore, any cycle variations can be assumed to result from external influences, rather than from the fuel itself. The viscosity of nano-fluid depends on the nanomaterial used when the fuel used is included in the class of nano-fluid [47]. Several factors that affect nanofluid viscosity include the particle size, temperature, particle concentration, stability, sonification time, surfactant addition, clustering effect, particle size, and dispersion techniques [48]. Therefore, the following hypothesis is GO included in fuel is inert to the combustion reaction and is also good for binding between gasoline and ethanol to reduce $COV_{P_{max}}$. However, as the viscosity of the fuel used increases, the pumping power required in the suction process increases [49].

RSM was used to analyze the amount of GO to decrease the COV efficiently. The RSM results displayed in [Figure 8b](#) show that the COV_{IMEP} values did not significantly change compared to the $COV_{P_{max}}$ values, as shown in [Figure 7b](#), in which the changes in the latter are more clearly visible. This can also be seen in the ANOVA response results in [Table 6](#), which shows the P-

values COV_{IMEP} of approximately 0.622. This is more than 0.05, which means it is not significant. However, the P-value from $COV_{P_{max}}$ was 0.0012, indicating a significant result when GO was added to the fuel with $COV_{P_{max}}$ decreasing. [Figure](#)

[7b](#) and [Figure 8b](#) show the RSM results; the regression model used is shown in [Table 7](#); corresponding for responses resulted in [Table 8](#), where A denotes the concentration of GO and B denotes engine speed.

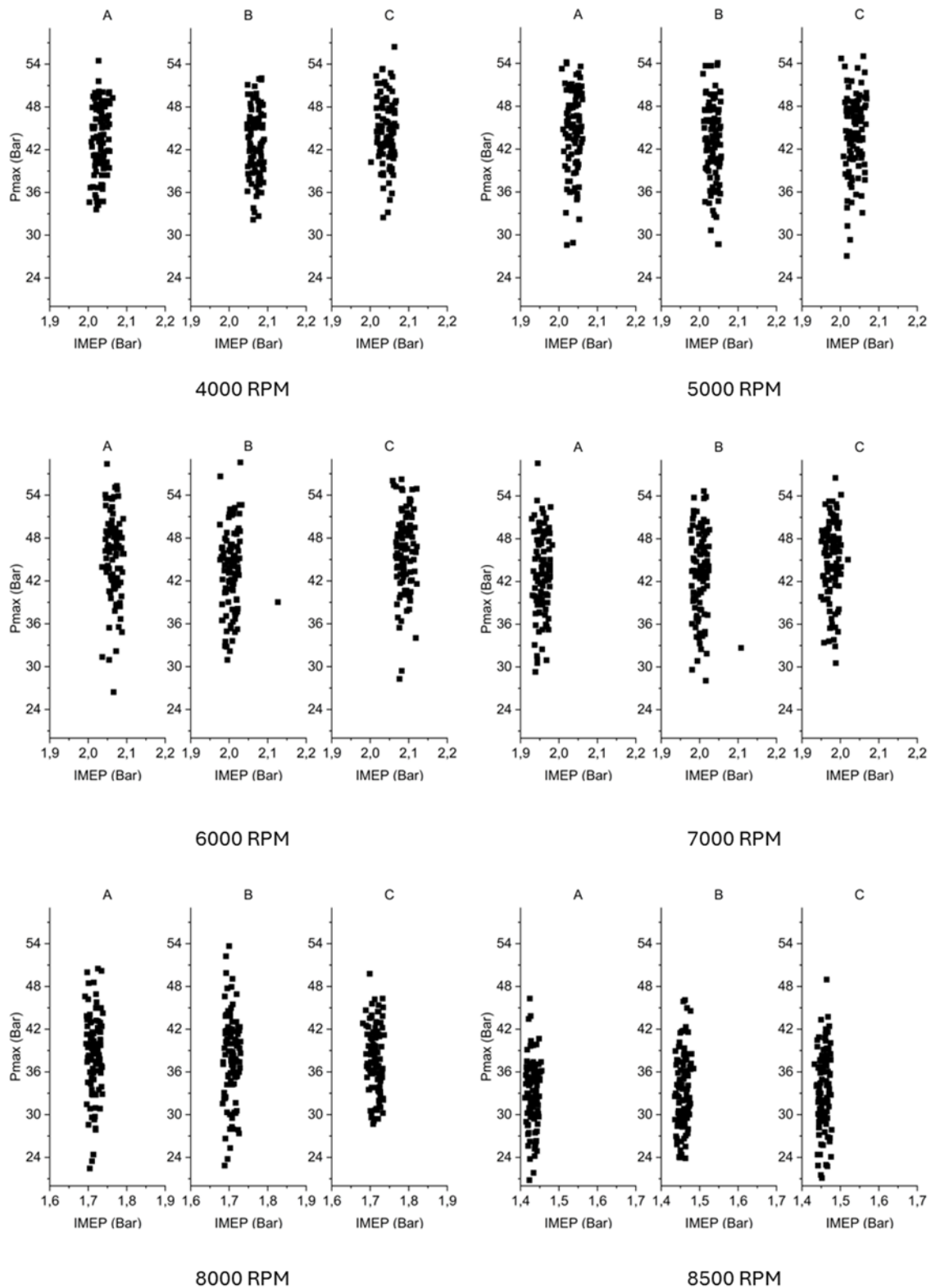


Figure 6. Comparison of IMEP value against P_{max} , in which the sample C fuel tends to be better able to maintain the IMEP value against the increase in engine speed (A=gasoline; B=E20; C=E20GO)

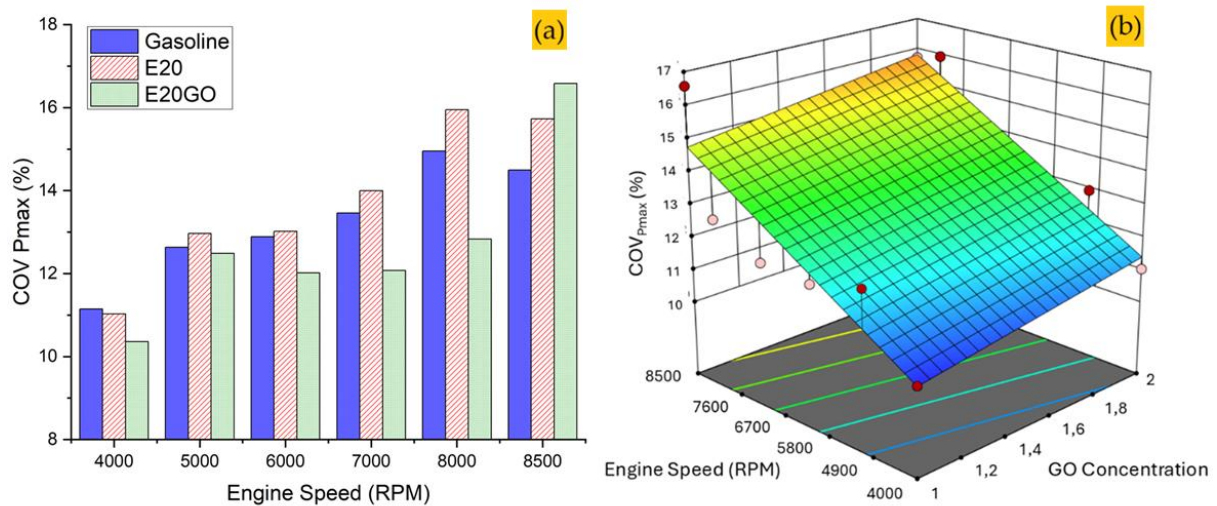


Figure 7. Actual COV_{Pmax} data for spark ignition engine with three different fuels (a) and COV_{Pmax} RSM optimization for E20 & E20GO (b), where a GO concentration value of 1 denotes 60 ppm and 2 denotes 0 ppm

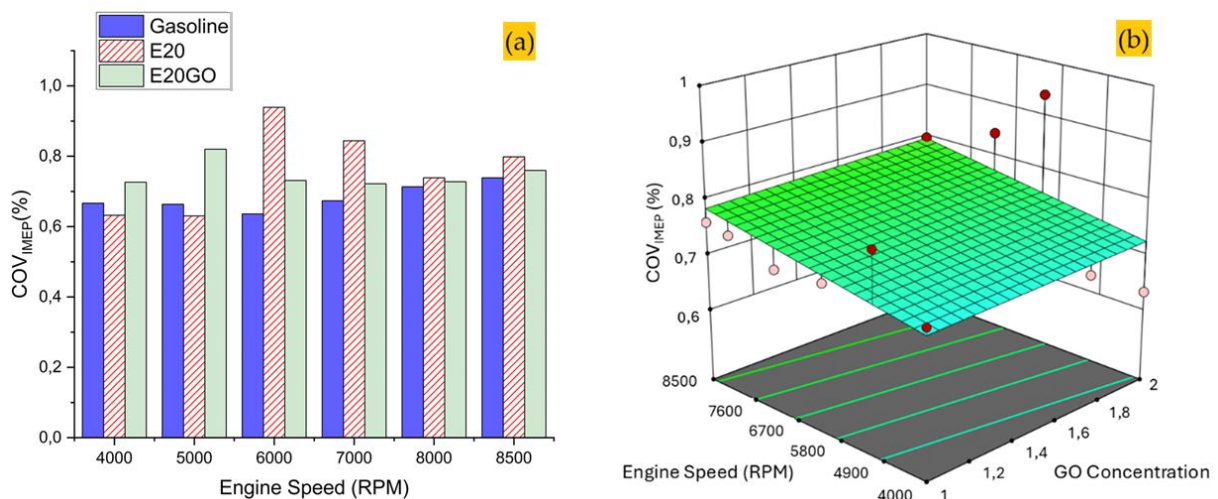


Figure 8. Actual COV_{IMEP} data for SI engine with three different fuels (a) and COV_{IMEP} RSM optimization for E20 & E20GO (b), where a GO concentration value of 1 denotes 60 ppm and 2 denotes 0 ppm

Table 6. Engine responses ANOVA from RSM method for two-factor interaction model

Responses	R ²	F-value	P-value
P _{max}	0.5957	6.63	0.017
CA at P _{max}	0.1817	0.0152	0.4056
COV _{Pmax}	0.777	15.68	0.0012
IMEP	0.6985	10.43	0.0045
COV _{IMEP}	0.1001	0.5004	0.6222

Table 7. Regression equation for engine response (A denotes GO concentration, dan B denotes engine speed)

Parameter	Value
P _{max}	= 55.18132 – 1.12277A – 0.002022B
CA at P _{max}	= 365.04212 + 0.083333A + 0.000299B
COV _{Pmax}	= 5.35745 + 1.05790A + 0.000983B
IMEP	= 2.65249 – 0.006607A – 0.000118B
COV _{IMEP}	= 0.637466 + 0.012129A + 0.000016B

Table 8. Predicted pressure engine object response (Fuel 1 denotes E20GO, and Fuel 2 denotes E20)

Run order	Fuel (Factor)	Engine speed (Factor)	COV _{Pmax}	COV _{IMEP}	P _{max}	CA at P _{max}	IMEP
1	1	4000	0.7132	10.35	45.97	366.32	2.17
2	1	5000	0.7291	11.33	43.95	366.62	2.05
3	1	6000	0.7450	12.31	41.92	366.92	1.94
4	1	7000	0.7609	13.30	39.90	367.22	1.82
5	1	8000	0.7768	14.28	37.88	367.51	1.70
6	1	8500	0.7848	14.77	36.87	367.66	1.64
7	2	4000	0.7253	11.41	44.85	366.40	2.17
8	2	5000	0.7412	12.39	42.82	366.70	2.05
9	2	6000	0.7571	13.37	40.80	367.00	1.93
10	2	7000	0.7730	14.36	38.78	367.30	1.81
11	2	8000	0.7889	15.34	36.76	367.60	1.69
12	2	8500	0.7969	15.83	35.74	367.75	1.63

However, as seen in [Figure 7b](#) and [Figure 8b](#), COV_{IMEP} did not decrease significantly, whereas COV_{Pmax} decreased significantly. Note that IMEP is measured at every 0.25-degree crank angle, making it more susceptible to fluctuations compared to P_{max}, which is measured at a single point, leading to different results. To visualize the intake process in an internal combustion engine, assumed the generated pressure is 1 bar, with another cycle exhibiting a deviation of 0.2 bar. This variation results in a high standard deviation. In contrast, during the work process where P_{max} is generated, assuming a pressure of 60 bars, a 0.2-bar deviation would lead to significantly lower standard deviation than in the intake process.

As a result, COV_{IMEP} which is calculated based on all points in one cycle, makes it challenging to determine whether the addition of GO effect the COV value derived from combustion pressure. Furthermore, combustion occurs over only 180 degrees of the cycle, while the remaining 270 degrees involve mechanical process without direct pressure influence from combustion.

3.3. Performance (Power & Torque)

The effect of GO is an increase in engine performance, as depicted in the data presented in [Figure 9](#). It is evident that in the medium engine speed range (4000-6000 RPM), the torque from the use of GO in the gasoline and ethanol mixture increases compared to the case of E20, and the torque of E20GO is slightly higher than that of pure gasoline, where the highest value is achieved at an engine speed of 5500 RPM with an increase of 5% from 8.049 Nm to 8.427 Nm. However, at high speeds (6000-8500), all fuels used, including

E20GO, E20, and pure gasoline, exhibited similar torque outputs. This result is due to the more consistent combustion pressure values, which contribute to maintaining engine stability. This observation aligns with the research conducted by Soudagar *et al.* [23], who also used GO as an additive in diesel engine fuel. However, GO itself possesses an extensive specific surface area, leading to a larger cross-sectional area for the fuel [29], which accelerates fuel evaporation. Consequently, the heat of vaporization increases, and the densities of the air and fuel can also increase [50]. Conversely, faster evaporation also results in quicker combustion of fuel and air. Another effect attributed to GO is reduced friction, which can prevent the formation of carbon and iron deposits [51].

As torque increases, higher power output is generated. Typically, the highest power output of an internal combustion engine is achieved at the highest RPM value, as shown in [Figure 9b](#). E20GO provided the highest power output at the highest peak power, which occurred at an engine speed of 7500 RPM. Gasoline and E20 follow this trend. However, the increase in power produced by the addition of GO compared to that which does not occur at engine speeds of 5500 RPM with an increase of 5% from 5.182 kW to 5.399 kW. The effect of GO on engine power also positively affects compressed ignition engines that use biodiesel fuel, increasing the generated power [52].

The heat release rates for combustion with GO blends at 4000 RPM and full load are shown in [Figure 10](#). [Figure 10a](#) reveals that E20GO has the shortest ignition delay, followed by gasoline and

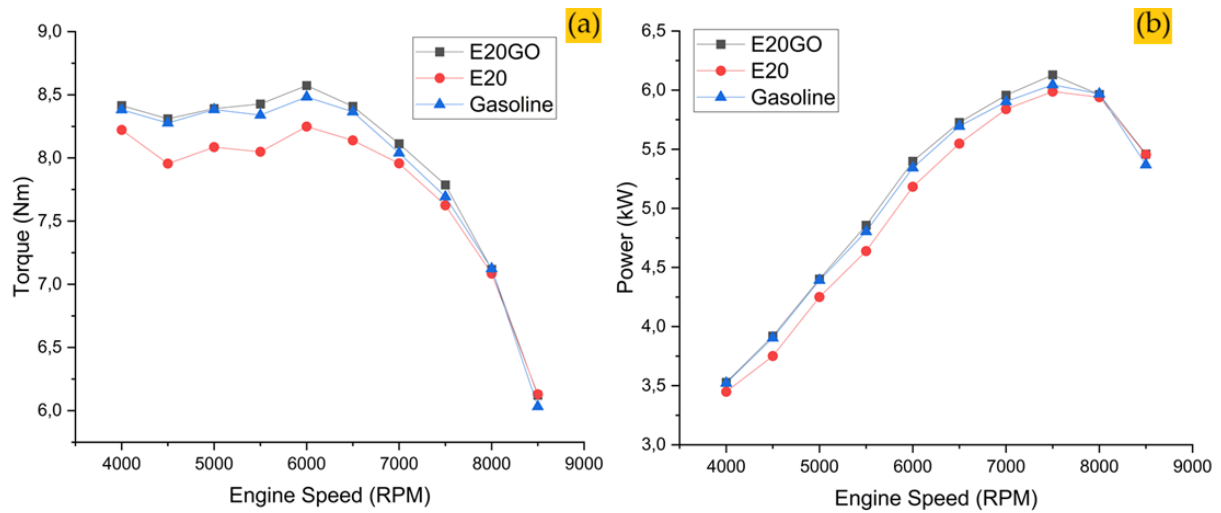


Figure 9. Performance for each fuel sample, E20GO fuel has engine torque (a) and engine power (b) values close to those of gasoline

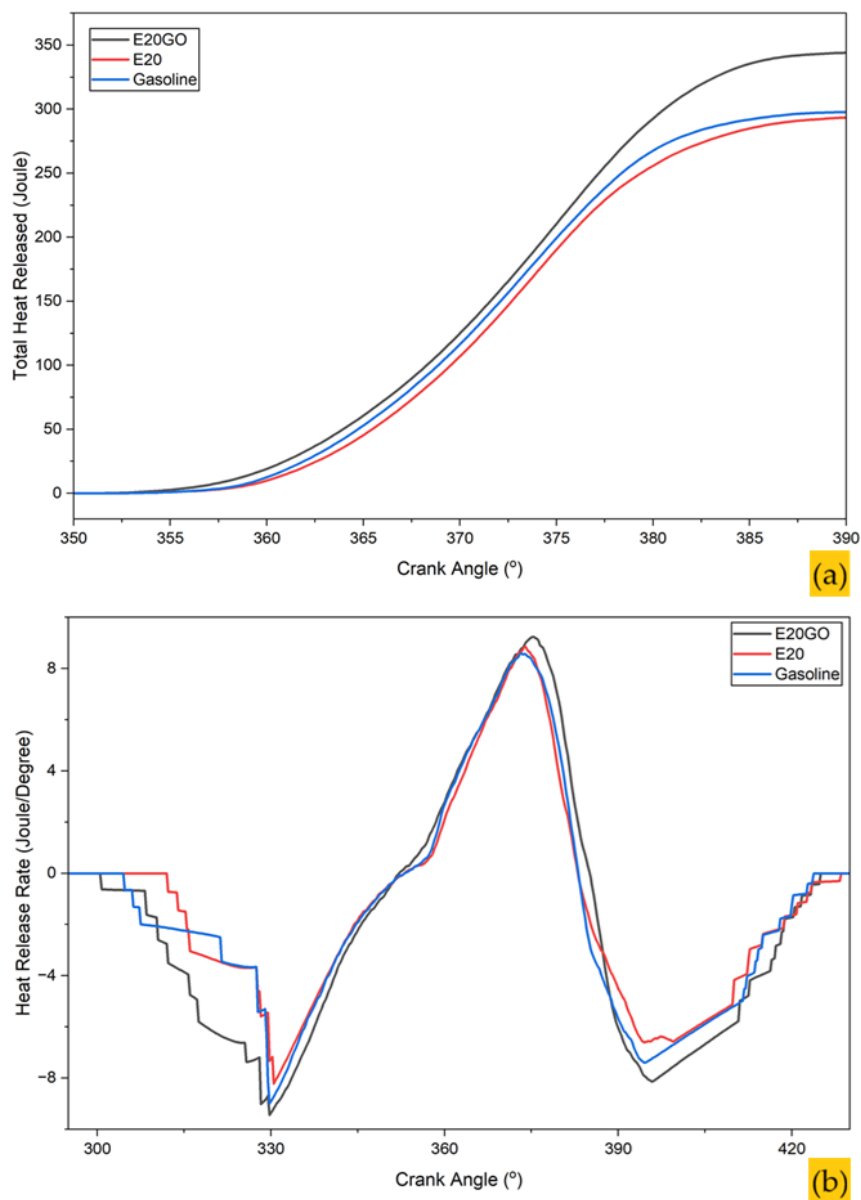


Figure 10. Total heat released (a) and heat release rate combustion (b) of E20GO at 4000 RPM

then E20, which has the longest delay. Compared to the other fuels, the E20GO blend yielded the greatest total heat release (338.43 Joule), while neat gasoline and the E20 blend released 297.89 Joule and 294.38 Joule, respectively. This trend is consistent with the measured power and torque outputs, for which the E20GO blend also recorded the highest values. A corresponding trend is evident in the heat release rate per degree (Figure 10b), where the E20GO blend demonstrates a higher rate, particularly at its peak. Similar to its effect in diesel engines, the addition of GO reduces the ignition delay, a phenomenon attributable to the nanomaterial's high thermal conductivity and large surface area [24], [53]. Graphene accelerates the combustion rate by promoting reactions within the air-fuel reaction zone, an effect driven by the catalytic activity of its oxygen functional groups [29].

3.4. Specific Fuel Consumption

The specific fuel consumption is a measure of the amount of fuel that can be converted into energy units per unit time per hour. In general, the SFC is expressed as the amount of fuel mass per unit of power at one time. It is an indirect measure of the efficiency of an engine running on a particular type of fuel. If the SFC value is high, it can be concluded that combustion is inefficient, and vice versa; if it is low, combustion is more efficient. Figure 11 shows the variations in SFC for each fuel type. From the presentation of the data, it can be observed that the SFC trend resulting from the use of E20GO, which includes a mixture of GO, increases fuel consumption compared to E20 and Gasoline. The highest increase compared to E20 was 15%, occurring at engine speeds of 8000 RPM and 8500 RPM where the value rose from 382.37 g/kWh to 438.4 g/kWh and from 426.13 g/kWh to 490.35 g/kWh respectively. Muralidharan *et al.* obtained similar results when GO was added to biodiesel, resulting in a 4.95% increase in fuel consumption and a 3.76% decrease in thermal efficiency [54]. The increase in SFC is attributed to excessive nanoparticle agglomeration, leading to an increase in fuel viscosity [33]. Nanoparticles exhibit an optimal concentration for improving combustion. Concentrations exceeding this optimum degrade performance due to the associated increase in fuel viscosity [55].

Excessive GO concentration leads to a chemical reaction with the engine oil, resulting in harmful deposits on integral engine parts, including valves, piston rings, injectors, piston crowns, and manifolds. These deposits can affect the flow of air and fuel, potentially leading to an increase in SFC, and consequently, a decrease in engine efficiency [54]. Furthermore, GO minimally affects calorific value but is included in the calculation of fuel that enters the combustion chamber, leading to more fuel passing through. Additionally, GO has a high thermal conductivity [29]; therefore, the heat released from the fuel is absorbed by the GO during the combustion process. That is, the heat that should be available for engine output is absorbed by the GO itself. This is evident from the exhaust temperature graph (Figure 12), in which the GO values were lower than those for E20. The most significant decline compared to E20 occurred

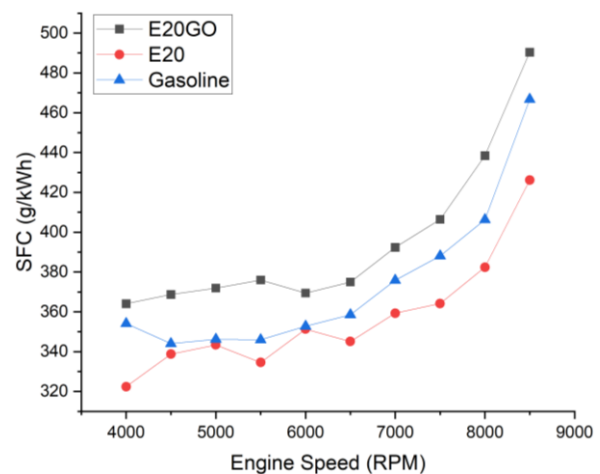


Figure 11. Specific fuel consumption for each fuel sample

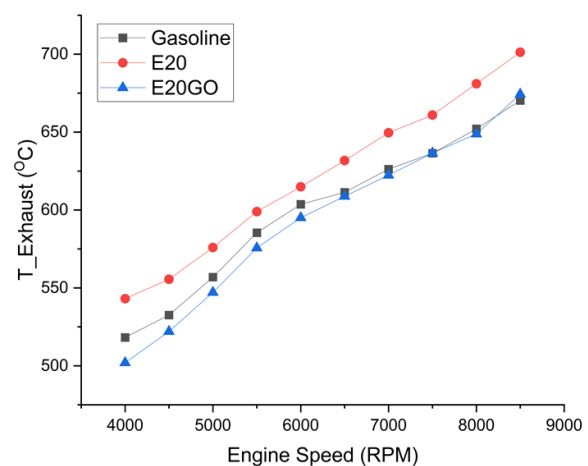


Figure 12. Exhaust temperature each fuel every engine speed

at engine speed of 4000 RPM with a reduction of 7.57% where the temperature decreased from 543.14 °C to 502.03 °C. In conclusion, it can be inferred that the released heat is absorbed by GO, meaning that not all the heat is utilized for the expansion process.

3.5. Emission and Environmental Aspect

CO₂ was used as an indicator of the completeness of combustion in the combustion chamber. The higher the CO₂ value, the more complete the combustion process, leading to increased thermal efficiency compared with that of gasoline fuel. This contrasts with CO emissions, where higher CO values indicate incomplete combustion. As shown in Figure 13a, the CO₂ emissions were the highest for the E20 sample, followed by E20GO, and were the lowest for gasoline. These CO₂ emission results were reinforced by CO emissions with an inverse pattern (Figure 13b), with the lowest emissions (in descending order) being E20, E20GO, and gasoline. Various factors contribute to the formation of CO, including the fuel-to-air ratio. Inadequate air or excess fuel can result in incomplete combustion, leading to increased CO emissions, particularly under low-load conditions or lower temperatures. The use of ethanol blends in gasoline typically decreases CO emissions. In light-duty vehicle engines, a concentration of 16% can result in a reduction in CO levels of up to 29% compared to the use of certified gasoline [56].

The adsorption of heat by GO leads to a decreased combustion temperature compared

with combustion without a GO mixture. This can be observed in Figure 12, as the E20GO mixture exhibited a lower exhaust temperature, which indicates a lower combustion temperature. Lower combustion temperatures result in increased CO formation [52] thus, E20GO fuel produces higher levels of carbon monoxide than the E20 and gasoline fuel samples. Furthermore, the excessive use of GO as an additive interferes with the combustion process by accelerating the agglomeration rate of the nano-additives, reducing the total surface area available for catalytic activity. The overuse of GO causes incomplete combustion and increases carbon monoxide emissions [57]. Similar results were observed in a study conducted by Muralidharan *et al.*, who discovered that the inclusion of GO as a nano-additive in diesel engines increased the level of CO emissions at higher concentrations. Conversely, lower GO concentrations in the fuel samples resulted in lower CO emissions [54]. In this case, it is likely that the high concentration of GO in the E20GO fuel mixture led to a higher concentration of CO compared with E20, despite the high load on the engine.

The emissions produced by the nanoparticles used as combustion additives simultaneously have positive and negative environmental implications [29], [58], and their structure remains unchanged before use. Graphene can still absorb toxic materials in the air owing to its large specific surface area. However, if graphene carrying these toxic materials enters biological systems, it can be dangerous. GO particles that do not burn are

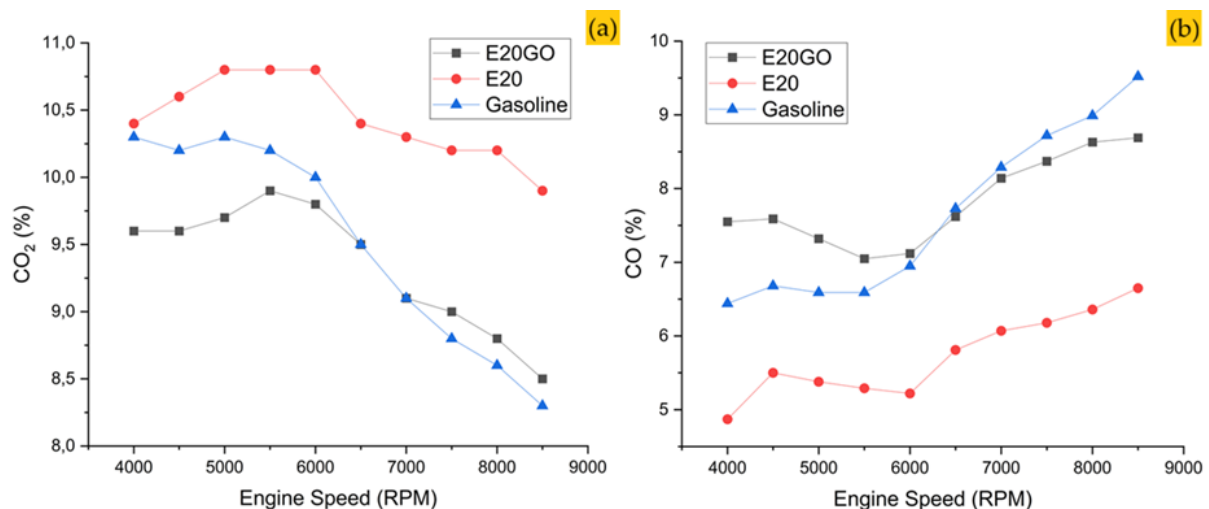


Figure 13. Exhaust emission each fuel sample, The CO₂ (a) trend of E20GO fuel is nearly identical to that of gasoline, similar to the CO (b) emissions

discharged into the air and are not visible to the naked eye. These particles are also hazardous to the human body because they can enter the respiratory tract without being noticed. However, further research in the health sector is needed to determine the dangers of GO to human health.

4. Conclusion

This research involved an experimental study of a single-cylinder spark-ignition engine installed on an engine dynamometer. The engine was operated and tested using gasoline-ethanol with GO nanoparticles synthesized from solid graphite. The experiment generated pressure data to understand the phenomenon of cylinder cycle variation using the COV approach. In addition, data on torque, power, and emissions were used.

As a result, the addition of GO can reduce COV due to its ability to bond with gasoline and ethanol, which have non-polar and polar properties, respectively. A significant decrease in $COV_{P_{max}}$ was observed with the addition of GO; in contrast, COV_{IMEP} was not significantly changed. This is possibly because P_{max} is measured at a single point with a high-pressure value as the basis for calculating combustion pressure variation, making it more sensitive for calculating COV than IMEP.

The effect of GO addition on power and torque generated a positive impact, as the power and torque trends concerning engine speed increased across nearly all engine speed points with the addition of GO. In addition, its fuel consumption was higher than that of E20. However, the emissions produced did not align with favorable outcomes regarding power and torque. The observed engine performance benefits signal viability for implementation; however, further consideration of ancillary factors is necessary for successful deployment. The use of GO also has the potential to harm the environment because despite its small size, it has a large specific surface that allows it to absorb toxic substances in the environment. This makes it dangerous if it enters the human respiratory tract, considering that GO does not oxidize in the combustion process. Its small size makes it easy to enter the respiratory tract, and it is not visible to the eyes.

Further studies should explore optimal GO concentrations and investigate emissions under transient engine conditions, as well as long-term

environmental effects of nanoparticle release. In addition, chemical kinetics studies are required to determine the effect of GO on the combustion reactions. In the fields of health and the environment, research must be conducted to determine the impact of GO on biological issues, especially in the respiratory tract.

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Author's Declaration

Authors' contributions and responsibilities

Askar Adika Agama: Conceptualization, Methodology, Writing – original draft; Ahmad Syihan Auzani: Investigation, Supervision, Writing – review and editing, approved the final manuscript; Alfian Ferdiansyah Madsuha: Methodology, Resource; Hendra Hermawan: Supervision, Writing – review and editing, approved the final manuscript; Ade Kurniawan: Validation, Data Curation; Mokhtar: Resource; Aswin: Software, Visualization; Nasruddin: Software, Supervision; Yulianto Sulistyo Nugroho: Supervision, approved the final manuscript; Harialdi: Funding Acquisition, Project administration, 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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