

# Experimental Investigation of Ethanol–Nanoparticle Blended Gasoline on Performance and Emission Characteristics of a Spark-Ignition Engine

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**Abstract.** The main objective of this study was to evaluate how ethanol concentration and aluminium oxide nanoparticle addition influenced the performance and exhaust emissions of a spark-ignition engine. These objectives were achieved by experimentally testing commercial petrol, gasoline containing 10% or 20% ethanol by volume, and the corresponding blends containing 10 or 20 parts per million of aluminium oxide at five engine speeds from 1700 to 3300 revolutions per minute. Brake thermal efficiency, brake-specific fuel consumption, carbon monoxide, unburned hydrocarbons, nitrogen oxides and carbon dioxide were evaluated. The most important results are that the highest brake thermal efficiency was 36.93% for the 20% ethanol blend containing 20 parts per million of aluminium oxide at 2900 revolutions per minute. The lowest brake-specific fuel consumption was 0.24 kg/kWh for commercial petrol at 2900 and 3300 revolutions per minute and for the 10% ethanol blend containing 10 parts per million of aluminium oxide at 3300 revolutions per minute. The minimum carbon monoxide concentration was 0.56%, the minimum unburned hydrocarbon concentration was 66 ppm, and the minimum nitrogen oxide concentration was 314 ppm, each under a different fuel and speed condition. The significance of the results lies in providing a controlled comparison of two ethanol concentrations and two nanoparticle dosages across the same operating range. Carbon dioxide emissions were higher for ethanol-containing blends than for commercial petrol and increased with engine speed. The findings show that responses depended on fuel formulation and engine speed, and no blend was best for every measured parameter.

**Keywords:** SI engine, ethanol–gasoline blends, nanoparticles, performance; emissions.

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## Studiu experimental privind efectele amestecării benzinei cu etanol și nanoparticule asupra performanțelor și emisiilor unui motor cu aprindere prin scânteie

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**Abstract.** Obiectivul principal al acestui studiu a fost evaluarea modului în care concentrația de etanol și adăugarea nanoparticulelor de oxid de aluminiu influențează performanțele și emisiile de evacuare ale unui motor cu aprindere prin scânteie. Acest obiectiv a fost atins prin testarea experimentală a benzinei comerciale, a amestecurilor de benzină cu un conținut de 10 % sau 20 % etanol (în volum) și a amestecurilor corespunzătoare care conțineau 10 sau 20 de părți per milion (ppm) de oxid de aluminiu, la cinci turații ale motorului, cuprinse între 1 700 și 3 300 rot/min. Au fost evaluate randamentul termic efectiv, consumul specific efectiv de combustibil, precum și emisiile de monoxid de carbon, hidrocarburi nearse, oxizi de azot și dioxid de carbon. Cele mai importante rezultate indică faptul că randamentul termic efectiv maxim, de 36.93 %, a fost înregistrat pentru amestecul cu 20 % etanol și 20 ppm de oxid de aluminiu, la o turație de 2 900 rot/min. Cel mai mic consum specific efectiv de combustibil, de 0.24 kg/kWh, a fost obținut pentru benzina comercială la turații de 2 900 și 3 300 rot/min, precum și pentru amestecul cu 10 % etanol și 10 ppm de oxid de aluminiu, la 3 300 rot/min. Cele mai mici concentrații înregistrate au fost de 0.56 % pentru monoxidul de carbon, 66 ppm pentru hidrocarburile nearse și 314 ppm pentru oxizii de azot, fiecare dintre aceste valori fiind obținută în condiții diferite de compoziție a combustibilului și de turație a motorului. Importanța rezultatelor constă în furnizarea unei comparații experimentale controlate între două concentrații de etanol și două doze de nanoparticule, în același interval de funcționare a motorului. Emisiile de dioxid de carbon au fost mai mari în cazul amestecurilor cu etanol decât în cazul benzinei comerciale și au crescut odată cu turația motorului. Concluziile studiului arată că răspunsul sistemului a depins de compoziția combustibilului și de turația motorului, niciun amestec nefiind optim pentru toți parametrii măsurați.

**Cuvinte-cheie:** motor de aprindere prin scânteie, amestecuri de etanol și benzină, nanoparticule, performanță, emisii.

### Экспериментальное исследование влияния бензина, содержащего смесь этанола и наночастиц, на рабочие и экологические характеристики двигателя с искровым зажиганием

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**Аннотация** Основной целью данного исследования была оценка влияния концентрации этанола и добавления наночастиц оксида алюминия на рабочие характеристики и состав отработавших газов двигателя с искровым зажиганием. Для достижения этой цели были проведены экспериментальные испытания с использованием товарного бензина, бензина с добавлением 10% или 20% этанола (по объему), а также соответствующих смесей, содержащих 10 или 20 частей на миллион (ppm) оксида алюминия, при пяти различных частотах вращения коленчатого вала (от 1700 до 3300 об/мин). Оценивались такие показатели, как эффективный термический КПД, удельный эффективный расход топлива, а также содержание оксида углерода, несгоревших углеводородов, оксидов азота и диоксида углерода в отработавших газах. К числу наиболее важных результатов относится то, что максимальный эффективный термический КПД (36,93%) был зафиксирован для смеси с 20% этанола и 20 ppm оксида алюминия при частоте вращения 2900 об/мин. Минимальный удельный эффективный расход топлива составил 0.24 кг/(кВт·ч); этот показатель был достигнут при использовании товарного бензина (на частотах 2900 и 3300 об/мин) и смеси с 10% этанола и 10 ppm оксида алюминия (на частоте 3300 об/мин). Минимальные концентрации компонентов отработавших газов составили: 0,56% для оксида углерода, 66 ppm для несгоревших углеводородов и 314 ppm для оксидов азота (каждый из этих показателей был достигнут при различных сочетаниях вида топлива и частоты вращения). Значимость полученных результатов заключается в возможности сопоставления данных для двух концентраций этанола и двух дозировок наночастиц в одинаковом рабочем диапазоне. Выбросы диоксида углерода при использовании смесей с этанолом были выше, чем при использовании товарного бензина, и возрастали с увеличением частоты вращения двигателя. Результаты исследования показали, что реакция двигателя зависела от состава топлива и частоты вращения, и ни одна из испытанных смесей не оказалась лучшей по всем оцениваемым параметрам одновременно.

**Ключевые слова:** двигатель с искровым зажиганием, этано-бензиновые смеси, наночастицы, эксплуатационные характеристики; выбросы.

## INTRODUCTION

The increasing demand for transportation energy, depletion of petroleum resources and growing concern about exhaust pollutants have promoted the development of alternative fuels for internal combustion engines. Improvement of efficiency and reduction of emissions are essential research targets since SI engines are still widely used in transportation and small-scale power generation applications. Alcohol–gasoline blends have been of considerable interest among alternative fuels since ordinary petrol engines may use modest alcohol concentrations with no major hardware modification. Goktaş et al. [1] evaluated the effects of alcohol fuels on performance, combustion and emissions of SI-engines. Ethanol is particularly interesting as a petrol blending component because of its renewable origin, high octane number, and oxygen content. It might increase knock resistance by improving octane and its oxygen content can influence fuel oxidation. Ethanol has a lower heating value than petrol, and can influence fuel consumption and engine performance as its concentration grows. Wang et al. [2] observed that the ethanol blending affects SI-engine behavior by increasing the octane number, the charge-cooling impact and the

reduced energy content. Thus, the effects of ethanol content should be investigated for specific engine operating conditions. Performance and emissions have been affected by ethanol content, as shown in experimental studies. Iodice et al. [3] tested petrol blends containing 10%, 20%, and 30% ethanol and saw reductions in CO and HC emissions compared to commercial petrol, with E20 exhibiting promising emission behaviour for the cold-start conditions studied. Mohammed et al. [4] studied E10, E20, E30 and E40 in a single-cylinder SI engine and reported variations in power, brake-specific fuel consumption and thermal efficiency with the ethanol content, and reductions in exhaust pollutants. These experiments establish the E10 and E20 as relevant ethanol-gasoline blends for performance and emission tests. Li et al. [5] investigated methanol-, ethanol- and butanol–gasoline blends in a port-fuel-injection SI engine under varying fuel ratios, equivalence ratios and engine loads. Their studies proved that ethanol–gasoline blends could lead to a reduction in HC emissions, although CO and NO<sub>x</sub> responses depend on operating conditions. In addition to mixing with alcohol, metal-oxide nanoparticles have been researched for their

possible impact on alternative fuels' performance and emissions. Amirabedi et al. [6] studied the  $\text{Mn}_2\text{O}_3$  nanoparticles in an ethanol–gasoline-fuelled SI engine whereas Thamilarasan et al. [7] studied the nanoparticle-assisted ethanol-blended gasoline. These investigations illustrate the significance of the use of ethanol–gasoline blends with nanoparticles, the nanoparticle material and fuel formulas are different from those discussed in the present study.  $\text{Al}_2\text{O}_3$  nanoparticles have also been studied in gasoline–alcohol SI-engine applications. Priyadarshini and Kumar [8] investigated gasoline–alcohol blends with 10 ppm of  $\text{Al}_2\text{O}_3$  nanoparticles at different engine speeds.  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  nanoparticles in gasoline–alcohol-based nanofuels were examined at various concentrations and engine speeds by Gundala and Domakonda [9]. These experiments show that the addition of  $\text{Al}_2\text{O}_3$  can affect the performance and emission characteristics of ethanol-containing gasoline fuels. But variances in ethanol concentration, nanoparticle dosage and engine operating circumstances make direct comparison across various research difficult. Therefore the current study presents a controlled experimental comparison of two ethanol concentrations and two  $\text{Al}_2\text{O}_3$  concentrations under the same SI-engine setup and operating range. The fuels tested were PG, E10, E20, E10A10, E10A20, E20A10 and E20A20 and tested at 1700, 2100, 2500, 2900 and 3300 rpm. BTE, BSFC, CO, HC,  $\text{NO}_x$  and  $\text{CO}_2$  were analysed under the same operating conditions. Thus, the novelty of the present study is not claimed as the first application of  $\text{Al}_2\text{O}_3$  nanoparticles with ethanol–gasoline fuel. Instead, a direct comparison of ethanol concentration and  $\text{Al}_2\text{O}_3$  dosage is provided within a common experimental matrix. The purpose is to evaluate their effects on engine performance and emissions and to find the best formulation under the conditions experimentally studied, without claiming a universal fuel optimisation.

## MATERIALS AND METHODS

### I. Fuel Preparation

The fuel used as a reference was commercial gasoline (PG). Ethanol was used as the oxygenated blending component. Two ethanol–gasoline blends, E10 and E20, were prepared on a volumetric basis with 10% and 20% ethanol, respectively.  $\text{Al}_2\text{O}_3$  nanoparticles were added to the ethanol–gasoline blends at concentrations of

10 and 20 ppm. Accordingly, the nanoparticle-assisted fuels were designated as E10A10, E10A20, E20A10 and E20A20, where A10 and A20 denote 10 and 20 ppm  $\text{Al}_2\text{O}_3$ , respectively.

The dispersion of  $\text{Al}_2\text{O}_3$  nanoparticles into the corresponding fuel blends was carried out using an ultrasonic probe sonicator, as shown in Fig. 2. Ultrasonication was performed for 30 min to promote homogeneous dispersion of the nanoparticles in the fuel blends and minimize particle agglomeration. The  $\text{Al}_2\text{O}_3$  nanoparticles used in the experimental study had an average particle size of approximately 40 nm, a specific surface area greater than  $40 \text{ m}^2/\text{g}$  and a purity greater than 99.9%. These specifications are consistent with the previously reported experimental work using the same experimental setup.

The prepared nano-fuel blends were stored in closed containers prior to the engine tests to minimize changes in fuel composition.



Fig. 2. Ultrasonication setup.

### II. Experimental Engine Setup

A computerized, single-cylinder, four-stroke, port-fuel-injection SI engine connected to an eddy-current dynamometer was used for the experiments. The test engine, dynamometer, fuel supply and measurement system, electronic control unit, load indication, temperature indicator and data-acquisition system comprised the experimental setup. Fig. 3 shows the experimental setup, and the specifications of the test engine are presented in Table 1.

The Honda GX200 engine was coupled to an eddy-current dynamometer and operated using a computerized data-acquisition system. The experimental setup included a fuel-measuring unit and engine-performance measurement system. Engine-performance data were acquired using IC Engine Soft, while exhaust emissions were measured using an AVL exhaust-gas analyser. The same experimental platform and

measurement arrangement have been reported in the earlier experimental investigation.

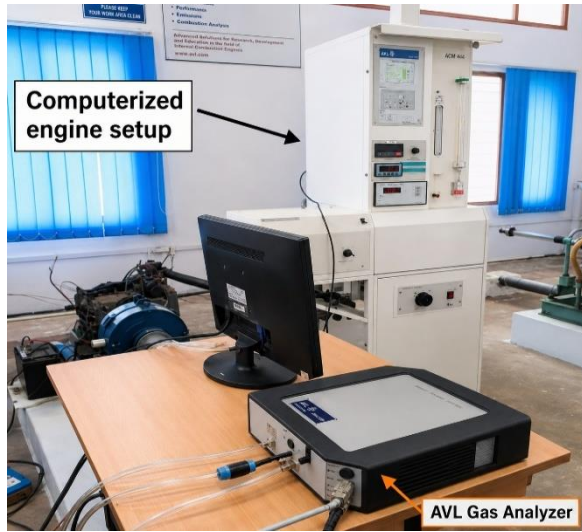


Fig. 3. Experimental setup of the SI engine.

Table 1. Specifications of the test engine.

| Parameter         | Specification                          |
|-------------------|----------------------------------------|
| Engine model      | Honda GX200                            |
| Engine type       | Single-cylinder, four-stroke SI engine |
| Fuel system       | Port fuel injection                    |
| Rated power       | 4.1 kW at 3600 rpm                     |
| Bore              | 68 mm                                  |
| Stroke            | 54 mm                                  |
| Compression ratio | 8.5:1                                  |
| Cooling system    | Air-cooled                             |
| Dynamometer       | Eddy-current dynamometer               |

### III. Experimental Procedure

The engine was permitted to reach a stable operating condition before each run. The prepared fuel was supplied to the engine, and the experiments were conducted at a constant part-load condition of 75%, corresponding to a dynamometer load of approximately 5 kg. The engine speed was varied at 1700, 2100, 2500, 2900 and 3300 rpm, while the other operating conditions were maintained consistently for all tested fuels.

PG, E10, E20, E10A10, E10A20, E20A10 and E20A20 were tested using the same experimental procedure to enable direct comparison of their performance and emission characteristics.

The engine-performance parameters, namely BP, BTE and BSFC, were obtained from the measured engine operating data using the IC Engine Soft system. Exhaust emissions were

measured using an AVL exhaust-gas analyser. The emission characteristics considered were CO, HC, NO<sub>x</sub> and CO<sub>2</sub>. The same measurement procedure was followed for all fuel formulations at each engine speed.

The obtained performance and emission data were subsequently analysed as a function of engine speed to evaluate the effects of ethanol concentration and Al<sub>2</sub>O<sub>3</sub> nanoparticle addition. The present investigation was conducted as a direct experimental comparison and no numerical optimization technique was applied. The primary objective was to evaluate the individual and combined effects of ethanol concentration and Al<sub>2</sub>O<sub>3</sub> nanoparticle concentration on the performance and exhaust emissions of the SI engine.

### IV. Uncertainty Analysis

The estimated uncertainties of the main experimental parameters are listed in Table 2. The overall uncertainty of the estimated parameters was calculated using the root-sum-square method:

$$U_R = \sqrt{\sum_{i=1}^n \left( \frac{\partial R}{\partial x_i} U_{x_i} \right)^2}$$

Based on the experimental uncertainties of  $\pm 1.0\%$  for BP,  $\pm 1.0\%$  for fuel consumption, and  $\pm 0.5\%$  for calorific value, the combined uncertainty can be estimated as

$$U_{BTE} = \sqrt{(1.0)^2 + (1.0)^2 + (0.5)^2} = 1.50 \%$$

Similarly, the uncertainty in BSFC was estimated from the uncertainties associated with fuel consumption and brake power:

$$U_{BSFC} = \sqrt{(1.0)^2 + (1.0)^2} = 1.41 \%$$

Table 2. Experimental uncertainty

| Parameter       | Range            | Uncertainty  |
|-----------------|------------------|--------------|
| BTE             | 25.11–36.93 %    | $\pm 1.50\%$ |
| BSFC            | 0.24–0.36 kg/kWh | $\pm 1.41\%$ |
| CO              | 0.56–5.21 %      | $\pm 5\%$    |
| HC              | 66–613 ppm       | $\pm 5\%$    |
| NO <sub>x</sub> | 314–2100 ppm     | $\pm 5\%$    |
| CO <sub>2</sub> | 5.11–21.50 %     | $\pm 5\%$    |

## RESULTS AND DISCUSSION

The results are discussed in terms of BTE, BSFC, CO, HC, NO<sub>x</sub> and CO<sub>2</sub> emissions to examine the influence of fuel composition and engine speed on the measured performance and emission characteristics. Only the experimentally tested fuel formulations are considered, and no numerical optimization is performed. Particular attention is given to the effects of ethanol concentration and Al<sub>2</sub>O<sub>3</sub> nanoparticle addition within the tested fuel matrix.

#### V. Brake Thermal Efficiency

Figure 4 depicts the variation of BTE with engine speed for the tested fuel formulations. BTE generally increased with engine speed up to 2900 rpm for most fuels, followed by a decrease at 3300 rpm. PG exhibited BTE values of 25.19%, 25.72%, 26.45%, 27.49% and 25.11% at 1700, 2100, 2500, 2900 and 3300 rpm, respectively. The ethanol-containing blends generally exhibited higher BTE than PG. Increasing the ethanol concentration from E10 to E20 improved BTE, with values increasing from 31.98% for E10 to 33.13% for E20 at 2900 rpm. The addition of Al<sub>2</sub>O<sub>3</sub> further increased BTE for the E20-based blends, with E20A10 and E20A20 achieving 36.71% and 36.93%, respectively, at 2900 rpm. The higher BTE observed with ethanol-containing blends may be associated with the oxygen content of ethanol, which can favour fuel oxidation [10]. The maximum BTE of 36.93% was attained with E20A20 at 2900 rpm, representing the highest value among the tested fuel formulations. The subsequent decrease in BTE at 3300 rpm was observed for most fuel formulations, indicating that the effect of engine speed was dependent on the fuel composition and operating condition [11].

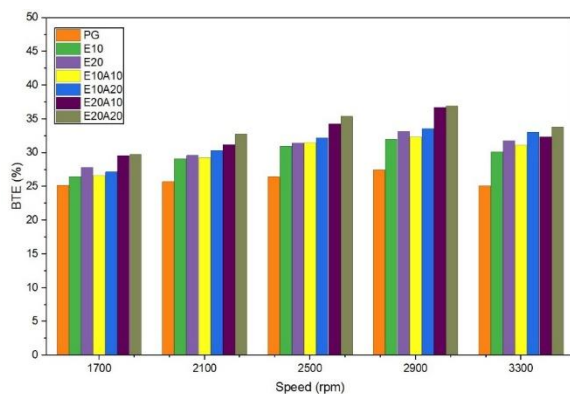


Figure 4. Variation of BTE with engine speed.

#### VI. Brake-Specific Fuel Consumption

Figure 5 demonstrates the variation in BSFC with engine speed for the tested fuel formulations. BSFC generally decreased with increasing engine speed for most of the tested fuels. PG showed a reduction in BSFC from 0.29 kg/kWh at 1700 rpm to 0.24 kg/kWh at 2900 rpm, which remained at 0.24 kg/kWh at 3300 rpm. The ethanol blends generally exhibited higher BSFC than PG, particularly at lower engine speeds, which may be associated with the lower energy content of ethanol [12]. The addition of Al<sub>2</sub>O<sub>3</sub> resulted in a reduction in BSFC for some fuel formulations and operating conditions. At 2500 rpm, BSFC decreased from 0.32 kg/kWh for E20 to 0.31 kg/kWh for E20A10, while E20A20 recorded 0.32 kg/kWh. At 2900 rpm, E10A20 recorded 0.26 kg/kWh compared with 0.29 kg/kWh for E10. However, the reduction was not consistent for all blends; at 3300 rpm, E20A10 and E20A20 recorded relatively higher BSFC values of 0.33 kg/kWh. The minimum BSFC of 0.24 kg/kWh was recorded for PG at 2900 and 3300 rpm and for E10A10 at 3300 rpm [13].

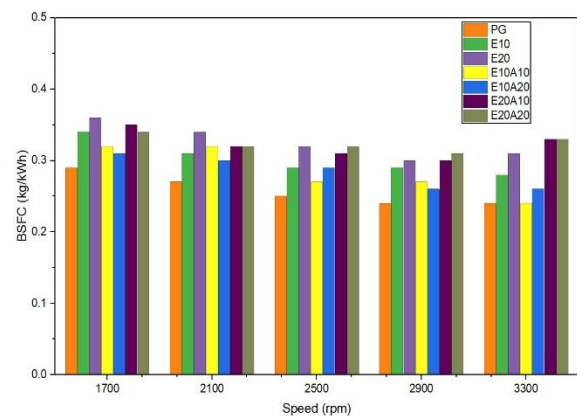


Figure 5. Variation of BSFC with engine speed.

#### VII. CO Emissions

Figure 6 shows the variation of CO emissions with engine speed for the tested fuel formulations. CO emissions generally decreased with increasing engine speed for all the tested fuels. PG exhibited the highest CO emission of 5.21% at 1700 rpm, which decreased to 1.71% at 3300 rpm. The ethanol-containing blends generally showed lower CO emissions than PG, with the reduction becoming more evident at higher engine speeds [14]. At 2900 rpm, CO decreased from 1.41% for E10 to 1.35% for E20, while the corresponding values for E10A10, E10A20, E20A10 and E20A20 were 1.27%, 1.11%, 1.01% and 0.96%, respectively. At 3300 rpm, E20A10 and E20A20 recorded the lowest CO values of 0.59% and 0.56%, respectively. The lower CO emissions

observed with the ethanol-containing blends may be associated with the oxygen content of ethanol, which can favour oxidation of carbon-containing species [15]. The further reduction observed for some  $\text{Al}_2\text{O}_3$ -containing blends indicates that the effect of nanoparticle addition was favourable under the corresponding operating conditions. The minimum CO emission of 0.56% was obtained with E20A20 at 3300 rpm.

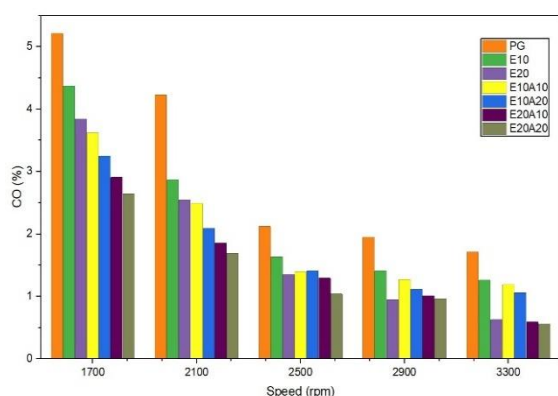


Figure 6. CO emissions with engine speed.

#### VIII. HC Emissions

Figure 7 shows the variation of HC emissions with engine speed for the tested fuel formulations. HC emissions generally decreased with increasing engine speed for all the tested fuels. PG decreased from 579 ppm at 1700 rpm to 203 ppm at 3300 rpm. At 1700 rpm, E20 recorded a higher HC emission of 613 ppm, whereas the addition of  $\text{Al}_2\text{O}_3$  reduced the HC emission to 590 ppm for E20A10 and 576 ppm for E20A20. With increasing engine speed, the ethanol-containing blends generally exhibited lower HC emissions. At 2900 rpm, HC decreased from 224 ppm for PG to 124 ppm for E20, while E20A10 and E20A20 recorded 119 ppm and 115 ppm, respectively. At 3300 rpm, the lowest HC values were observed for E10A20 (66 ppm) and E20A20 (71 ppm). The reduction in HC with increasing engine speed and the lower values observed for several ethanol- and  $\text{Al}_2\text{O}_3$ -containing blends may be associated with improved oxidation of unburned hydrocarbons [16].

#### IX. NO<sub>x</sub> Emissions

Figure 8 shows the variation of NO<sub>x</sub> emissions with engine speed for the tested fuel formulations. NO<sub>x</sub> emissions generally increased with engine speed up to 2900 rpm for most fuel formulations, followed by a decrease at 3300 rpm. PG increased from 1603 ppm at 1700 rpm to 1992 ppm at 2900 rpm and further to 2100 ppm at 3300 rpm [17]. The ethanol-containing blends showed considerable variation in NO<sub>x</sub>

emissions depending on ethanol and  $\text{Al}_2\text{O}_3$  concentration.

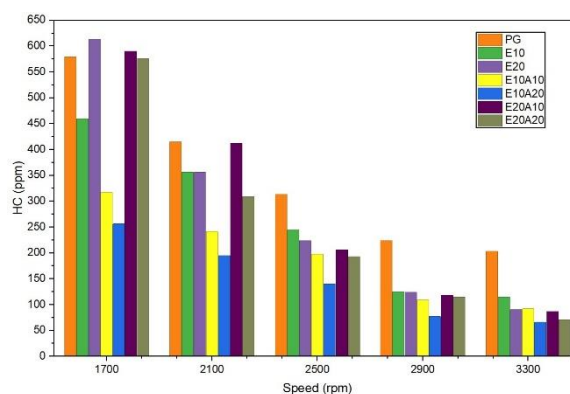


Figure 7. HC emissions with engine speed.

At 1700 rpm, E20, E20A10 and E20A20 recorded substantially lower NO<sub>x</sub> emissions of 350, 339 and 314 ppm, respectively, compared with 1603 ppm for PG. At 2900 rpm, PG recorded 1992 ppm, while E20, E20A10 and E20A20 each recorded 1985 ppm. At 3300 rpm, E20A20 recorded 1815 ppm compared with 2100 ppm for PG. These results indicate that the influence of ethanol and  $\text{Al}_2\text{O}_3$  addition on NO<sub>x</sub> emissions varied with engine speed and fuel composition. Since in-cylinder combustion parameters were not measured in the present study, the specific mechanism responsible for the observed NO<sub>x</sub> variation cannot be directly established [18].

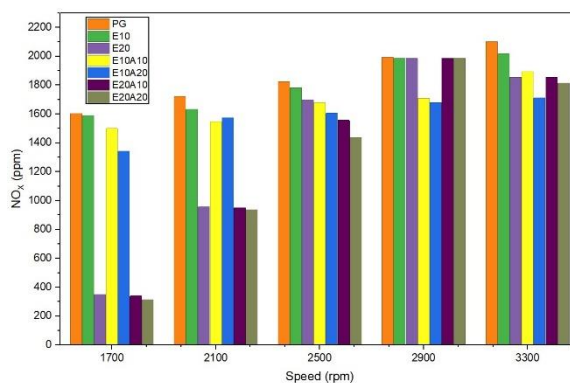


Figure 8. NO<sub>x</sub> emissions with engine speed.

#### X. CO<sub>2</sub> Emissions

Figure 9 shows the variation of CO<sub>2</sub> emissions with engine speed for the tested fuel formulations. CO<sub>2</sub> emissions generally increased with increasing engine speed for all the tested fuels. PG increased from 5.11% at 1700 rpm to 8.58% at 3300 rpm. The ethanol-containing blends generally recorded higher CO<sub>2</sub> emissions than PG, with E20 showing the highest values among the tested fuels at higher engine speeds [19]. At 2900 rpm, CO<sub>2</sub> increased from 8.24% for PG to 17.30% for E20, while E20A10 and E20A20 recorded 17.00% and 17.55%, respectively. At 3300 rpm,

E20 recorded 20.50% and E20A20 recorded 19.56%, compared with 8.58% for PG. The increase in CO<sub>2</sub> with ethanol-containing blends indicates greater conversion of carbon-containing species to CO<sub>2</sub> under the tested operating conditions. The observed CO<sub>2</sub> response varied with ethanol concentration, Al<sub>2</sub>O<sub>3</sub> addition and engine speed [20].

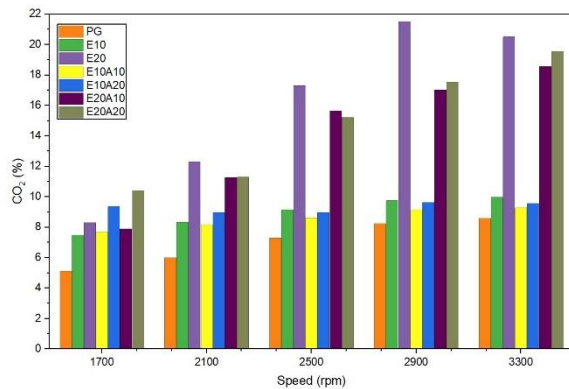


Figure 9. CO<sub>2</sub> emissions with engine speed.

## CONCLUSIONS

This experimental study investigated the effects of ethanol concentration and Al<sub>2</sub>O<sub>3</sub> nanoparticle addition on the performance and emission characteristics of a spark-ignition engine over the tested engine-speed range. Increasing the ethanol concentration from E10 to E20 generally improved BTE, with the maximum BTE of 36.93% obtained for E20A20 at 2900 rpm. The addition of Al<sub>2</sub>O<sub>3</sub> improved BTE for several operating conditions, although its effect varied with fuel composition and engine speed. The BSFC results showed that nanoparticle addition did not produce a consistent reduction for all fuel formulations, with the minimum BSFC of 0.24 kg/kWh recorded for PG at 2900 and 3300 rpm and E10A10 at 3300 rpm. CO emissions decreased with increasing engine speed, and the minimum CO value of 0.56% was obtained with E20A20 at 3300 rpm. HC emissions also generally decreased with increasing engine speed, with the minimum value of 66 ppm obtained for E10A20 at 3300 rpm. NO<sub>x</sub> emissions varied with fuel composition and engine speed; the lowest value of 314 ppm was recorded for E20A20 at 1700 rpm. CO<sub>2</sub> emissions generally increased with engine speed, with higher values observed for the ethanol-containing blends than for PG. Overall, E20A20 provided the highest BTE and favourable CO and HC emission characteristics under several of the tested conditions. However, its performance was not uniformly superior for all

measured parameters, and therefore it should not be considered an optimized formulation. The findings indicate that the combined use of ethanol and Al<sub>2</sub>O<sub>3</sub> can influence SI-engine performance and emissions, with the response depending on fuel composition and operating speed.

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