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Performance and Emissions of Spark-Ignition Internal Combustion Engine Operating with Bioethanol–Gasoline Blends at High Altitudes Under Low- and High-Speed Conditions

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Abstract: Several countries have cities located at elevations above 2000 m. Consequently, the internal combustion engines (ICEs) that operate there do not achieve the desired performance and emissions under these atmospheric conditions. One approach to mitigate these effects and, at the same time, address climate change is the use of biofuel–fossil fuel blends. However, ICEs must operate under a wide range of rpm to meet varying workload demands, raising concerns that these fuel blends may not be fully effective in achieving the desired performance and emission outcomes under such conditions. To address this issue, a series of experimental tests were conducted at low and high rpm of a spark-ignition (SI) ICE fuelled with bioethanol–gasoline blends in the ratios of E10, E15, E20, E40, E60, E85, and E100. The tests were conducted at 2600 m above sea level (masl) under various engine loads. The E20 and E40 blends showed outstanding performance at 2700 rpm, achieving high brake power and low emissions of CO_2 and HCs. At 4300 rpm, the E40 blend exhibited great performance because the engine produced high brake power and low emissions of CO and NOx. Based on these results, it can be concluded that bioethanol concentrations of between 20 and 40% in the blend effectively compensate for the reduced atmospheric oxygen at high altitudes, enhancing the combustion process in SI-ICEs.

Keywords: emissions; bioethanol–gasoline blends; SI-ICE; performance

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1. Introduction

Internal combustion engines (ICEs) are the thermal machines most used for transportation, power generation, and other applications such as pumps, lawnmowers, etc. Their performance and emissions are influenced by several factors, notably fuel quality and atmospheric conditions. Fuel composition and the oxygen density in the atmosphere influence optimal fuel oxidation. Variations in altitude can thus significantly affect engine performance and pollutant emissions, leading to higher fuel consumption and greater environmental impacts [1].

Many large cities globally are situated at elevations above 2000 m above sea level (masl), where reduced atmospheric oxygen levels affect the operation of ICEs. Additionally, they frequently operate outside their optimal rpm range and at partial loads. These conditions increase fuel consumption and the emissions of harmful exhaust gases like nitrogen oxides (NOx) and particulate matter in the engine [2]. These pollutants contribute to air quality degradation, posing serious environmental and public health risks in urban areas due to prolonged exposure to these emissions, which are associated with respiratory issues and other health complications, diminishing the quality of life of the affected populations [3]. Different government entities report that the emissions produced in these cities mostly come from gasoline ICEs [4].

Until sectors reliant on ICEs for their operation achieve full decarbonization through complete electrification or by adopting innovative technologies such as mobile carbon capture and storage systems for synthetic fuel production [5–8], regulatory agencies must address this global issue by consistently enhancing fuel quality. However, achieving this transition requires great efforts from all sectors involved in this issue, such as transportation, shipping, and heavy industry.

One of the most widely adopted measures worldwide to improve the combustion processes of ICEs and reduce the carbon footprint is to blend gasoline with bioethanol in a proportion of around 10% (depending on the country) [9–12]. Nevertheless, these measures have not been sufficient to reduce harmful emissions due to the large number of vehicles and machines that still use gasoline ICEs as a powertrain [13]. Therefore, and until all productive sectors are electrified, it is necessary to continue researching solutions to address this issue. One promising avenue in the short term is finding particular blends of bioethanol with gasoline so that ICEs can achieve suitable performance with reduced harmful emissions since it has been demonstrated that an increase in bioethanol in the blend compensates for the lack of oxygen in the atmosphere when the engines operate at high altitudes [14].

In recent years, different experimental tests have been conducted on the performance and emissions of gasoline engines fuelled with bioethanol–gasoline blends. The results show that engines fuelled with bioethanol–gasoline blends present lower brake power, torque, and brake-specific fuel consumption values than those fuelled with neat gasoline. Regarding the emissions, these research works reported a significant reduction in the values of harmful emissions such as carbon monoxide (CO) and hydrocarbons (HCs) and an increase in nitrogen oxides (NOx) [15–23]. Similar results have been found in gasoline engines operating at high altitudes. However, the brake thermal and volumetric efficiency values obtained are comparable to those reported in sea-level experimental tests [14,24].

Nevertheless, these results do not fully represent the operational characteristics of engines, as the experimental tests were conducted at a single speed point, varying only the engine load. This approach does not accurately reflect actual operation conditions, where engines typically operate at lower RPM to minimize fuel consumption, leading to different performance and emission profiles [25]. Therefore, it is essential to investigate the non-ideal operating conditions of engines fuelled with bioethanol–gasoline to obtain comprehensive information regarding their performance and emissions, particularly at elevated sea levels.

For this reason, this study was focused on evaluating the behaviour of a gasoline engine operating at low and high speeds (2700 and 4300 rpm), with several engine loads, fuelled with several bioethanol–gasoline blends (E10, E15, E20, E40, E60, E85, and E100), to obtain the regulated emission results of NOx, HCs, CO, and CO_2 and the performance of the engine. This work aims to understand and extend the knowledge about the regulated emissions and performance of an SI-ICE operating at high altitudes and high and low rpm. In this way, a more suitable gasoline–bioethanol blend for work under these conditions can be determined to meet the stringent emission regulations and fuel economy targets established by different regulatory agencies.

2. Materials and Methods

2.1. Engine Test Rig

Experimental tests were carried out with an unmodified, four-stroke, naturally aspirated gasoline engine, with a single cylinder, spark ignition, compression ratio of 8.5:1, displacement volume of 242 cc, and fuel supply with a carburettor. The experimental test rig featured a braking system that operated through electric resistors connected to an electric generator. These resistors allowed for fine adjustments of 100 W and supported a maximum load of 10 kW. Engine speed (rpm) was measured using a 725N-3000P/R reference encoder (Idaho, USA), while a K-type thermocouple recorded the exhaust gas temperature. The signals from these instruments were acquired using a 6212 reference data acquisition card from National Instruments (NI) (Texas, USA). Additionally, the experimental test rig included a Pitot tube anemometer with an EXTECH HD350 (New Hampshire, USA) for measuring intake air speed. Gas analysis was conducted using a GASBOX gas analyser (Treviso, Italy), which measures CO, CO_2, HC, NOx, and O_2 concentrations, and the fuel mass was measured with a digital scale. Finally, experimental data were recorded using NI-LabVIEW 8 software. A schematic representation of the experimental test rig and a photograph of the actual setup are shown in Figure 1, and Table 1 presents the main characteristics of all measuring instruments.

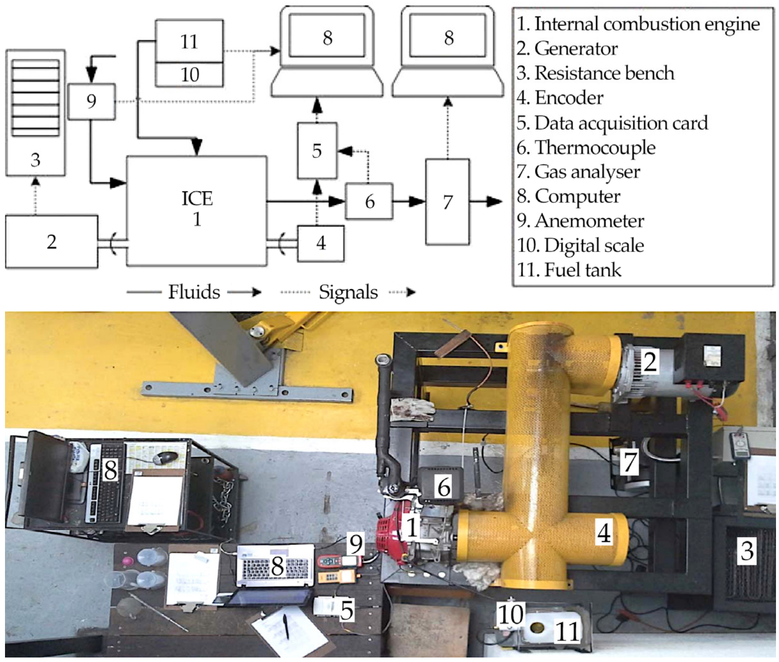

Figure 1. Engine test rig.

Table 1. Measurement instruments.

Instrument	Brand	Reference	Resolution
Digital scale (Quebec, Canada)	ACCULAB	VICON	0.1 g
Encoder	EPC	725N-3000P/R	0.1 rpm
Data acquisition card	NI	6212	16 bits
Thermocouple type K	NA	NA	0.1 °C
Pitot tube and digital anemometer	Extech	HD350	0.01 m/s
Gas analyser	TEXA	GASBOX	0.1% (CO_2) 0.01% (CO, O_2) 1 ppm (HCs, NOx)

A repeatability test of the test rig was conducted utilizing E10 fuel (which is the baseline fuel), during which a total of 10 measurements were taken over several days and under varying climatic conditions. Variables such as the brake mean effective pressure (BMEP), brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and emissions of CO, CO_2, HCs, and NOx were determined through an analysis of the propagation of uncertainty, as detailed in [26]. This process began with direct measurements based on the instruments' sensitivity. Subsequently, the uncertainty for indirect measures was calculated using the partial derivative method. The results of this uncertainty analysis, along with the relative errors, are presented in Table 2.

Table 2. Uncertainty of experimental measurements.

Measurement	Uncertainty [+/−%]
Brake mean effective pressure, BMEP	8.02
Brake-specific fuel consumption, BSFC	9.06
Brake thermal efficiency, BTE	9.06
CO_2 emissions	1.37
CO emissions	7.69
NOx emissions	10.00
HC emissions	7.69

2.2. Fuels

The fuels used were E10 gasoline and 98% anhydrous bioethanol; the fuels' properties are presented in Table 3. The lower heating value (LHV) was calculated from the data of pure gasoline and bioethanol [27]. The density was measured for both fuels using a hygrometer (resolution of 5 kg/cm^3). These tests were conducted in the hydraulic and fluids laboratory of the Fundación Universitaria Los Libertadores.

Table 3. Fuel properties.

Property	Gasoline E10	Bioethanol	Test Method
LHV [kJ/kg]	42,870	27,000	ASTM D240 [28]
Density [kg/m^3]	720	785	ASTM D4052 [29]
Research octane number	92.3	108.6	ASTM D2699 [30]
Motor octane number	83.7	99.9	ASTM D2700 [31]

2.3. Experimental Method

The experimental tests were conducted using bioethanol–gasoline blends in volume proportions of 10, 15, 20, 40, 60, 85, and 100% bioethanol (designated as E10, E15, E20, E40, E60, E85, and E100). This procedure was carried out using calibrated test tubes. The selected rotational speeds for the tests were at maximum torque (2700 rpm), representing a suitable rpm point below the rpm that produces the maximum engine power output, and above the maximum power (4300 rpm) to evaluate engine performance and emissions at high speeds. Both points were tested across several partial engine loads in terms of the BMEP. This approach allows for comparing the two scenarios and facilitates the mapping of the engine's behaviour.

The experimental tests on the engine began with the blend with the lowest LHV, i.e., E100; when the engine reached stable rotational speeds (2700 or 4300 rpm) with each specific engine load, measurements were conducted. The test points for each blend were determined by running the engine at the maximum load condition for the test speed. This maximum load was then divided between 2 or 6 partial loads according to the brake system's available load settings, always trying to obtain the maximum test points for each blend. In the case of the blends with a lower LHV, specifically E100 and E85, the engine could not reach high load conditions. Consequently, between 2 and 3 measurement points were taken under these circumstances, depending on the rpm conducted.

The experiments were conducted at 2600 m above sea level (atmospheric pressure of 75 kPa). Before each fuel change, the fuel lines were thoroughly drained for each blend change. Subsequently, a new fuel was introduced, and the engine was operated for at least 30 min to ensure the purging of any residual fuel from previous experiments. A total of 67 engine operating points were analysed, considering load, fuel, and rpm variations. Each operating condition was tested thrice on different days to ensure repeatability, resulting in 201 experimental tests.

2.4. Variables Assessed

The engine load is represented by the brake mean effective pressure (BMEP), a standardized measure of engine power that is independent of engine size (Equation (1)). The BSFC is calculated using Equation (2), which relates the fuel mass consumed and the brake power. The second performance parameter is the BTE (Equation (3)), which is a dimensionless parameter calculated with the ratio of the measured brake power and the energy available in the fuel consumed. This relation is affected by combustion efficiency (η_c), which is estimated using the measured CO_2 in the exhaust gases vs. the stoichiometric CO_2. The BTE indicates how much of the energy of the fuel burned is transformed into useful mechanical energy in the crankshaft.

$$\text{BMEP} = W_b / V_d \tag{1}$$

$$\text{BSFC} = \dot{m}_f / \dot{W}_b \tag{2}$$

$$\text{BTE} = \dot{W}_b / LHV \dot{m}_f \eta_c \tag{3}$$

The specific emissions are analysed as combustion indicators of the engine. The brake-specific emissions are evaluated, corresponding to the chemical species of CO_2, CO, NOx, and HCs ($BSCO_2$, BSCO, BSNOx, and BSHCs). These are calculated using the measured percentage or parts per million of the chemical species in the exhaust gases and the brake power. Equation (4) is utilized to calculate each specific emission, where XX denotes the quantitative measure of the respective emission type [25].

$$\text{BSXX} = \dot{m}_{XX} / \dot{W}_b \tag{4}$$

3. Results

3.1. Brake-Specific Fuel Consumption

Figure 2 shows the BSFC values obtained in the experimental tests for several bioethanol–gasoline blends with the SI-ICE operating at 2700 and 4300 rpm. As anticipated and consistent with what was reported in the literature [32], the BSFC at both rpm decreases as the BMEP increases. Consequently, the BSFC curves for each blend are organized according to their respective LHV values, meaning that blends with higher energy per unit mass require less fuel mass for the same power output. Therefore, the highest BSFC in the SI-ICE is presented for E100 (blend with the lower LHV), while with E10, the SI-ICE presents the lowest BSFC (blend with the higher LHV).

At 4300 rpm, the values for the BSFC for all blends are much higher than at 2700 rpm. Likewise, the engine cannot reach the same power output as at 2700 rpm, so there is less BMEP at 4300 rpm. This tendency is expected since the engine, working at 4300 rpm, has little time to burn all the fuel. Thus, it does not use all available energy, leaving more energy in the exhaust gases than at 2700 rpm.

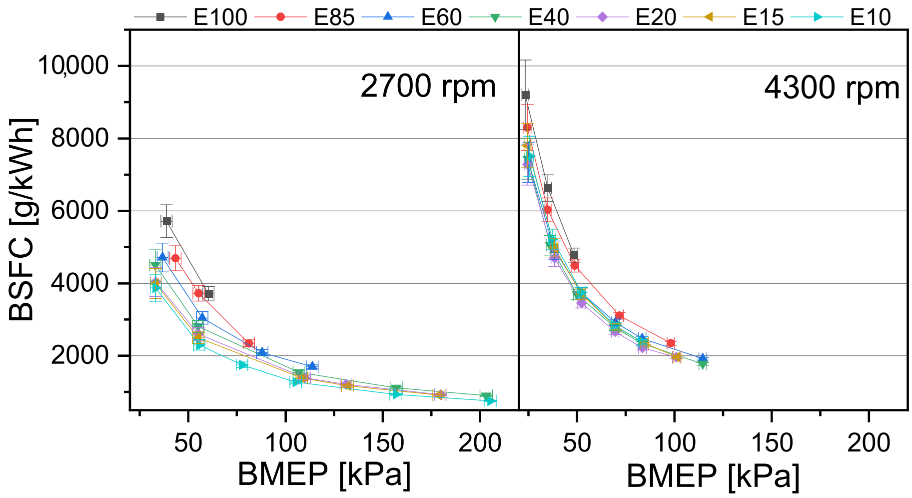

Figure 2. BSFC vs. BMEP at 2700 and 4300 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

3.2. Brake Thermal Efficiency

The BTE is the ratio of how much of the energy released by burning fuel is transformed into mechanical work, thus being an excellent indicator of the engine's work conditions. Figure 3 shows the results of the BTE as a function of the BMEP for 2700 and 4300 rpm. This figure shows that the BTE values increase for both speeds as the BMEP increases. This behaviour is because each blend's LHV is a constant value, while the BSFC decreases (Figure 2).

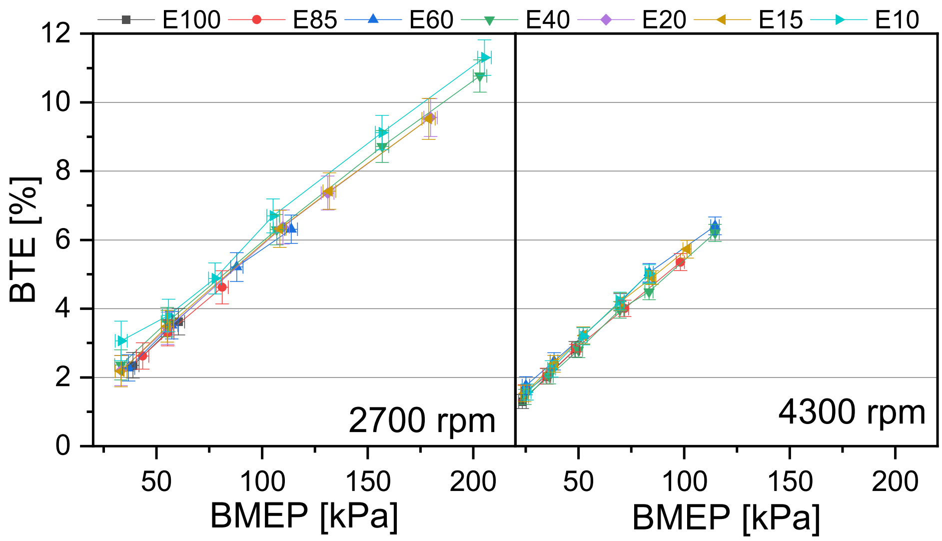

Figure 3. BTE vs. BMEP at 2700 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

As shown in Figure 3, the better values correspond to the blends that present lower fuel consumption. The overall highest BTE is presented by E10 and the lowest by E100; this aligns with the results obtained for the BSFC. However, the SI-ICE fuelled with E40 displays a BTE comparable to that fuelled with E10, being the second, overall, highest for most of the interval, indicating that a better combustion for E40 leads to a better thermal efficiency than that for E15 or E20, which are blends with a higher LHV and therefore a lower BSFC under this engine speed condition. The BTE results for 4300 rpm are almost half the values obtained for 2700 rpm. This behaviour is expected due to the higher fuel consumption at 4300 rpm.

3.3. Brake-Specific Carbon Dioxide

$BSCO_2$ emissions serve as a key indicator of combustion efficiency in the engine, reflecting the extent of the combustion process. During complete combustion, exhaust gases predominantly comprise CO_2, N_2, and H_2O. In contrast, incomplete combustion produces CO, HCs, and O_2. These byproducts utilize available carbon and oxygen, reducing CO_2 formation and limiting the engine's brake power output [33]. Therefore, achieving stoichiometric CO_2 is desirable in the combustion process, indicating complete combustion. Under such conditions, the fuel releases all its stored energy.

Figure 4 shows the $BSCO_2$ at 2700 and 4300 rpm for the tested fuel blends. The $BSCO_2$ emissions for all blends and engine speeds demonstrate a decreasing trend as the BMEP increases. Under these conditions, the E100 blend exhibits the highest $BSCO_2$ levels, while E10 yields the lowest. The blends E15, E20, and E40 display comparable $BSCO_2$ emissions at high BMEP values at 2700 rpm; this behaviour can be attributed to the higher octane number of bioethanol, which offsets the LHV as the bioethanol proportion in the blend increases. This compensation facilitates a more efficient combustion process, enabling the engine to achieve higher BMEPs. At 4300 rpm, all blends present higher $BSCO_2$ values than at 2700 rpm, resulting from the reduced brake power output achieved at this higher engine speed.

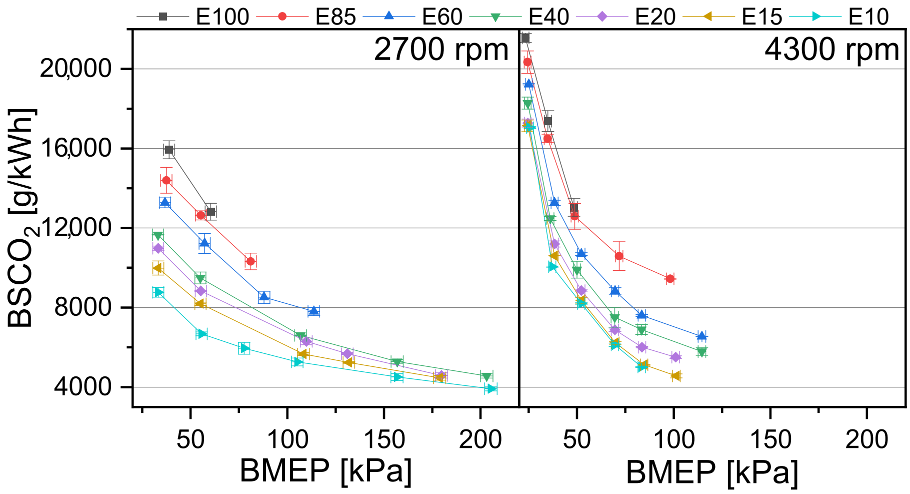

Figure 4. $BSCO_2$ vs. BMEP at 2700 and 4300 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

3.4. Brake-Specific Carbon Monoxide

Carbon monoxide is an incomplete combustion product with a very high toxicity [34] and is highly undesirable in the engine's exhaust gases. The oxygen in the bioethanol molecule is intended to compensate for the lack of atmospheric oxygen due to the high altitude. With this additional oxygen, CO emission turns into the emission of CO_2, improving combustion, increasing the energy released, and leaving better exhaust gases in the atmosphere. Nevertheless, the oxygen content is not the only parameter that regulates the formation of CO and CO_2. The LHV, combustion temperature, and air–fuel ratio play a principal role in forming chemicals during combustion [35].

Figure 5 presents the brake-specific carbon monoxide (BSCO) emissions at 2700 and 4300 rpm. At 2700 rpm, the general trend is that all blends exhibit high CO emissions at low power, reduced CO levels at a medium engine load, and an increased CO concentration at full load. Notably, with E100, E85, and E60, the engine shows the lowest CO emissions and a decreasing trend; this is because the engine fuelled with these blends cannot reach maximum brake power outputs. The E10 and E15 blends show an initial sharp decline in CO emissions as the brake power increases, followed by a slower decrease at mid-power and a sharp rise in CO emissions at maximum power. For the E20 and E40 blends, the engine achieves the maximum BMEP with favourable BSCO emission values.

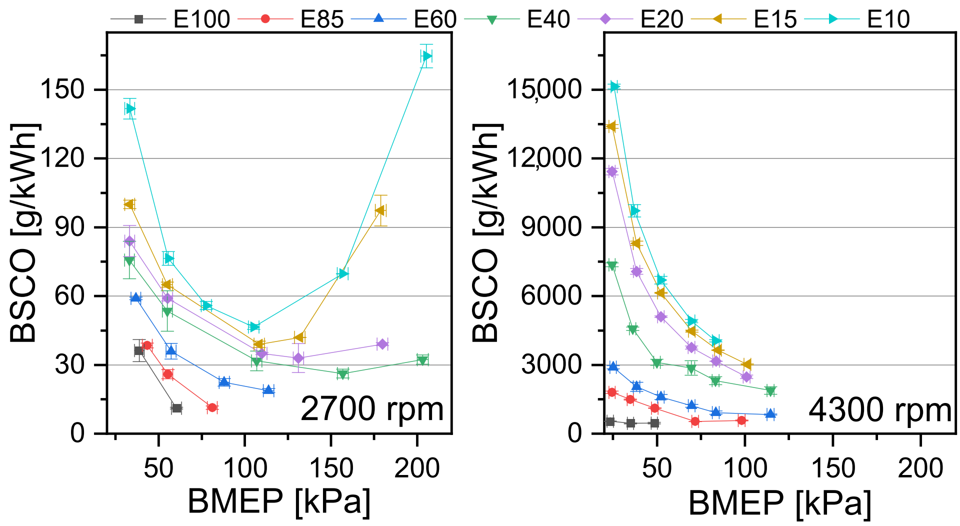

Figure 5. BSCO vs. BMEP at 2700 and 4300 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

This figure also displays that the BSCO emissions at 4300 rpm are almost 100 times higher than at 2700 rpm; this coincides with the above. The piston exhibits a higher average speed than at 2700 rpm; consequently, the combustion process is incomplete, despite the extra O_2 supply by the bioethanol, resulting in increased HC emissions released into the atmosphere. The engine fuelled with E10 produces the highest BSCO levels, followed in descending order by E15, E20, E40, E60, E85, and E100, which produce the lowest BSCO emissions.

3.5. Brake-Specific Nitrogen Oxides

Nitrogen oxides are formed when, due to high temperature, the N_2 molecule breaks, and the atomic nitrogen reacts with the available oxygen atoms or molecules, forming NO or NO_2 [36]. Therefore, in the combustion process, NOx emissions are a function of exhaust temperature and the available oxygen [37]. Engines working in stochiometric conditions produce lower BSNOx; nevertheless, when they reach high brake powers, they usually have high exhaust temperatures and increased NOx emissions. Therefore, when an engine operates with some proportion of bioethanol in the fuel, an extra amount of oxygen is available for the combustion process that, at high altitudes, compensates for the lack of atmospheric oxygen, increasing the combustion efficiency and increasing the exhaust temperature.

The experimental data on BSNOx at 2700 and 4300 rpm are presented in Figure 6. At 2700 rpm, the behaviour of nitrogen oxides is fractionated into two groups. The blends with high bioethanol, specifically E100, E85, and E60, exhibit low maximum brake power and very low NOx emissions. This trend is due to the low LHV of these blends, which produces lower exhaust temperatures, thereby inhibiting NOx formation. In contrast, blends with a lower bioethanol content (E40, E20, E15, and E10) demonstrate higher BSNOx emissions at low engine loads, followed by a decrease as the BMEP rises. This reduction is attributed to increased brake power output as the engine load intensifies.

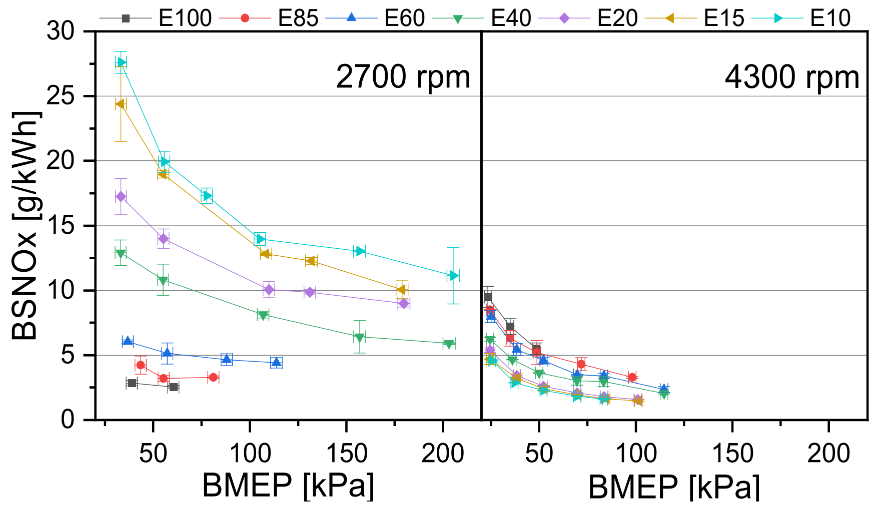

Figure 6. BSNOx vs. BMEP at 2700 and 4300 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

Regarding 4300 rpm, the BSNOx are lower than at 2700 rpm due to the lower engine brake power and poor combustion achieved at this operation point, which leads to lower exhaust gas temperatures (Figure 7). A particular behaviour is highlighted under this condition; all blends' BSNOx results are reversed, i.e., the highest NOx emission is with blend E100, and the lowest is with blend E10. This behaviour is because the extra oxygen contributed by the blends is not consumed in the combustion process. This leads to a rise in NOx emissions with the increase in bioethanol in the blend.

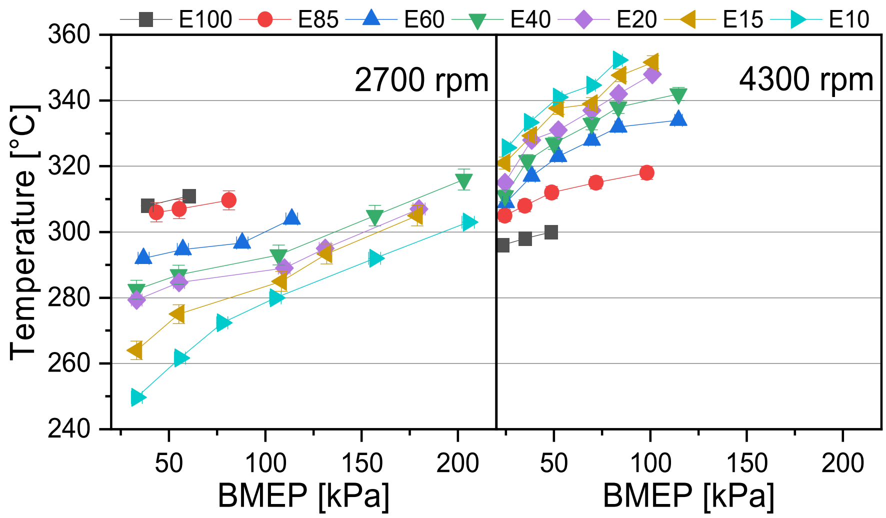

Figure 7. Exhaust gas temperature vs. BMEP at 2700 and 4300 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

3.6. Brake-Specific Hydrocarbons

The brake-specific hydrocarbons (BSHCs) in the exhaust are a product of incomplete combustion that occurs when the amount of oxygen is not enough to burn all the fuel in the combustion chamber or when the time for combustion is insufficient for the thermo-chemical reaction of all hydrogen, carbon, and oxygen present. High-altitude conditions tend to increase the BSHCs due to the lower atmospheric oxygen available, and the bioethanol in the blend is supposed to give the extra oxygen necessary for the reaction, decreasing the BSCO and BSHCs in exhaust gases. Nevertheless, the emission of HCs depends on other parameters, mainly the efficiency of combustion and the air–fuel ratio for each blend in the engine.

Figure 8 shows the BSHC emissions at 2700 and 4300 rpm. The results show that E10 presents the maximum BSHCs for these engine speeds, and all blends show a decreasing HC behaviour as the engine load increases. Also, it is observed that at 4300 rpm, the engine produces higher values of BSHCs than at 2700 rpm for all blends; as was mentioned before, this behaviour is due to the short time that the air–fuel has to react at 4300 rpm, meaning that not all of the fuel can burn, leading to a rise in the HC emissions. In both cases, the data dispersion of E85 and especially E100 was much higher than that of the other blends, showing a poor combustion process and some instability in the combustion efficiency and, thus, in engine operation.

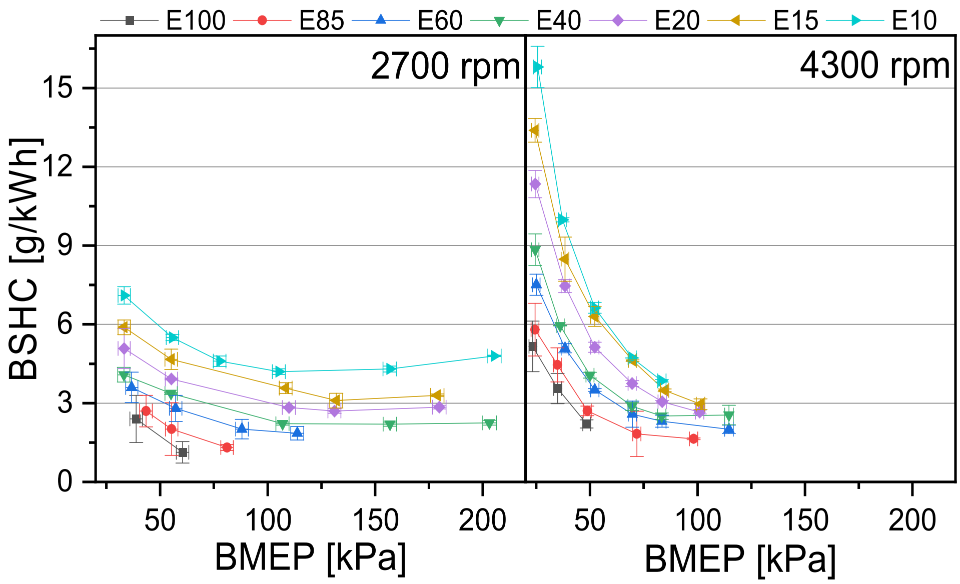

Figure 8. BSHCs vs. BMEP at 2700 and 4300 rpm of an SI-ICE fuelled with bioethanol–gasoline blends.

4. Discussion

Tables 4 and 5 illustrate the percentage of variation in each evaluated variable concerning E10 for both rpm. The data comprise both negative and positive values. A negative value denotes a reduction in the respective variable, while a positive value indicates an increase compared to E10.

Table 4. Percentage variation in key indicators at 2700 rpm.

Blend	BSFC	BTE	$BSCO_2$	BSCO	BSNOx	BSHCs
E100	54.51	−13.96	86.85	−79.91	−88.51	−72.83
E85	39.04	−10.97	75.61	−72.86	−83.20	−65.65
E60	26.73	−8.03	52.69	−57.70	−73.47	−52.66
E40	19.66	−8.62	26.90	−50.23	−47.68	−46.07
E20	8.92	−14.24	25.75	−29.47	−31.74	−29.93
E15	6.82	−14.26	14.72	−20.23	−8.21	−15.71

Table 5. Percentage variation in key indicators at 4300 rpm.

Blend	BSFC	BTE	$BSCO_2$	BSCO	BSNOx	BSHCs
E100	25.76	−13.03	52.72	−94.95	133.28	−66.13
E85	19.09	−10.25	59.03	−85.72	124.98	−57.57
E60	−0.23	−9.39	32.50	−77.69	92.91	−46.82
E40	−1.86	−9.56	20.92	−48.45	61.25	−39.44
E20	−6,70	−5.50	9.23	−24.19	15.37	−23.51
E15	−0.84	0.32	1.19	−10.69	5.46	−9.36

At 4300 rpm (Table 4), there is an increase in the BSFC for all blends, ranging from 7% to 55%, with a progressive rise as the bioethanol content in the blend increases. Conversely, at 2700 RPM (Table 3), no significant variation is observed for blends ranging from E15 to E60 compared to E10; however, for blends E85 and E100, an increase in the BSFC of between 19% and 26% is observed. Similar behaviour has been reported in the literature [26], where blends with a low bioethanol content exhibit slight variations in the BSFC, while those containing 50% bioethanol or more demonstrate higher fuel consumption. In the case of the BTE, it is observed that at 2700 and 4300 rpm, all the values decrease compared to E10 (less so in E15 at 2700 rpm), ranging from 5% to 14%. Notably, the blends E40 and E60 experienced a smaller reduction at both rpm.

The $BSCO_2$ for all blends increases compared to E10. Specifically, E100 exhibits the highest increase, 87% above E10 at 2700 rpm and 53% at 4300 rpm, while E15 shows the lowest increase, 1% at 4300 rpm and 14% at 2700 rpm. The pronounced difference in the $BSCO_2$ for blends with a lower bioethanol content can be attributed to the lower BMEP generated by the engine when operating with these blends compared to the others. Notably, the highest $BSCO_2$ values were recorded at these low-BMEP conditions; therefore, the largest differences among the blends were obtained at a low engine load. Regarding the BSCO and BSHCs, they present reductions and have similar variations concerning engine operation with E10. At 2700 and 4300 rpm, these reductions are in the order of 70% with the engine operating with E100, while with E15, there are reductions of 20% at 2700 pm and 10% at 4300 rpm compared to the engine operating with E10. This behaviour shows that increased bioethanol in the blend enhanced the engine's combustion process, reducing the CO and HC emissions. Finally, these tables present the percentage comparison of BSNOx regarding E10. It can be seen that the engine operating at 2700 rpm produces lower NOx emissions as the percentage of bioethanol in the blend increases, obtaining reductions from 8% with E15 to 89% with E100. This coincides with other research findings which have shown that the emissions produced in an SI-ICE fuelled with E10 and E20 for the overall speed range were higher than in that fuelled with pure gasoline [38,39]. However, at 4300 rpm, the NOx produced by the engine have an inverse behaviour, i.e., there is an increase in the values with the rise in bioethanol content in the blend. This increase goes from 5% with E15 to 130% with E100.

The results generally reveal an increase in $BSCO_2$ and a reduction in BSCO and BSHCs for all blends compared to E10 under both speed conditions. This is mainly caused by the fact that the additional oxygen supplied by these blends offsets the lower atmospheric oxygen. Therefore, less air is required in the intake manifold as the blend's bioethanol content rises; this reduction in the air mass can be seen in Table 6.

Table 6. Engine air mass flows in kg/h for each blend at the lowest engine load condition.

Blend	At 2700 rpm	At 4300 rpm
E10	21.6	32.0
E15	18.9	30.4
E20	18.8	28.4
E40	18.1	24.8
E60	17.0	22.7
E85	14.2	21.6
E100	10.5	19.8

Nevertheless, increasing the blend's bioethanol percentage poses several difficulties, chief among them being the constraints and sustainability issues related to its manufacturing. This would demand a significant increase in the availability of raw materials and raise questions regarding the viability and environmental effects of such production. Corn and sugarcane, which are categorized as first-generation biofuel feedstocks, are used to manufacture the majority of bioethanol [40]. However, since these crops are vital to the world's food supply, reliance on food-based raw materials raises moral and practical concerns.

Increased competition for resources and arable land could lead to higher food prices and greater food insecurity, a risk associated with expanding bioethanol production from first-generation feedstocks [41]. To solve this issue, future bioethanol production must move away from food-based sources. Second-generation bioethanol, which is produced from lignocellulosic materials such as forestry waste, agricultural waste, and certain biomasses, offers a more environmentally friendly choice [42,43].

Making the switch to second-generation bioethanol is difficult compared to first-generation bioethanol. Second-generation bioethanol requires complex processing methods and technologies, which are currently more expensive. Regulatory backing, technological advancement, and research expenditures must overcome these obstacles to achieve a suitable production of second-generation bioethanol. This aligns with international objectives to lower carbon emissions and maintain food security.

5. Conclusions

This study investigated the performance and emission characteristics of bioethanol–gasoline blends in an unmodified SI-ICE engine operating at two engine speeds (2700 and 4300 rpm) and high altitudes. The analysis focused on how the different bioethanol–gasoline ratios influenced engine key variables: BSFC, BTE, $BSCO_2$, BSCO, BSNOx, and BSHCs.

E20 and E40 show outstanding performance at 2700 and 4300 rpm since they achieve the highest BMEP above 200 kPa with middle values of BSFC and $BSCO_2$ and low values of BSHCs, BSCO, and BSNOx regarding the engine operation with E10. This demonstrates that the rise in bioethanol in the blend improves the engine's performance at high altitudes.

The results show that the increase in bioethanol in the blend counters the lack of atmospheric oxygen, improving the combustion process at the tested speeds and atmospheric conditions. The fuel's oxygen content enables the engine to enhance the burn of the air–fuel ratio, transforming more chemical energy into thermal and mechanical energy.

Higher bioethanol in the blend for both engine operation conditions is not suitable due to the fuel's low LHV, leading to poor engine performance (less than 100 kPa of BMEP) despite achieving lower values of harmful specific emissions (CO, HCs, and NOx).

The findings of this study demonstrate that an increase in bioethanol to up to 40% in gasoline blends enhances engine performance and reduces emissions at high altitudes, achieving a suitable balance between performance and emissions, delivering a high BMEP with moderate BSFC and $BSCO_2$ levels while minimizing harmful emissions (BSHCs, BSCO, and BSNOx). However, excessive bioethanol proportions in the blend negatively impact engine performance due to the fuel's lower LHV.

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Abbreviations

The following abbreviations are used in this manuscript:

BMEP	Brake mean effective pressure
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
$BSCO_2$	Brake-specific carbon dioxide
BSCO	Brake-specific carbon monoxide
BSNOx	Brake-specific nitrogen oxides
BSHCs	Brake-specific unburned hydrocarbons
ICE	Internal combustion engine
SI	Spark ignition
LHV	Lower heating value

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