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Evaluating Gasoline Engine Performance and Emissions with n-Butanol/gasoline Fuel Mixtures

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This study evaluates the performance and emission characteristics of a single-cylinder, four-stroke, air-cooled gasoline engine (Honda GX200D QX) fueled with n-butanol/gasoline blends (B10G90, B20G80, and B30G70) at varying engine loads (25%, 50%, 75%, and 100%). Experiments were conducted using a computerized engine test setup equipped with an eddy current dynamometer and advanced data acquisition systems. The blends were selected to assess the impact of increasing n-butanol content on critical performance parameters, including brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and combustion characteristics, as well as emissions, such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2). The results revealed that the addition of n-butanol improved combustion efficiency and reduced CO and HC emissions due to its higher oxygen content and improved combustion properties. However, increased n-butanol content slightly elevated BSFC due to its lower calorific value compared to gasoline. NOx emissions exhibited varying trends influenced by the enhanced combustion temperature at higher loads. These findings indicate that n-butanol/gasoline blends offer a promising alternative for reducing emissions and improving fuel sustainability in spark-ignition engines, aligning with global efforts toward cleaner transportation technologies.

Keywords: n-butanol, gasoline performance, emissions.

1. Introduction

Alcohol fuels like butanol are gaining attention as potential alternatives to gasoline in spark ignition (SI) engines due to their renewable nature and favorable combustion characteristics. Butanol, in particular, has been shown to enhance engine performance and reduce certain emissions when blended with gasoline. Studies have demonstrated that butanol-gasoline blends increase flame speed, combustion burn rate, and brake thermal efficiency, while reducing CO and HC emissions, although they may increase NO emissions[1]. The molecular structure of butanol isomers also plays a significant role in combustion performance, with linear chain isomers like 1-butanol providing more stable flame kernels and superior engine performance compared to branched isomers[2]. Additionally, the use of bio-butanol in combination with hydrogen has been explored, showing improvements in flame development and propagation phases, as well as reductions in CO and HC emissions, although NOx emissions may increase due to higher peak temperatures[3]. Innovative injection strategies, such as combined port and direct injection of n-butanol, have been found to optimize combustion and emission performance, with specific injection ratios yielding the best results[4]. Furthermore, the integration of HHO (oxyhydrogen) with butanol direct injection systems can mitigate the negative effects of butanol's high latent heat of vaporization, enhancing engine performance and reducing emissions[5]. Overall, butanol presents a promising alternative fuel for SI engines, offering potential environmental and performance benefits without requiring significant engine modifications. Butanol, as an alternative fuel in spark ignition (SI) engines, exhibits several beneficial effects on combustion and emission characteristics. Studies have shown that butanol-gasoline blends enhance flame speed, combustion burn rate, and pressure, leading to increased brake thermal efficiency compared to pure gasoline[6]. The molecular structure of butanol isomers significantly influences combustion performance, with linear chain isomers like 1-butanol providing more stable flame kernels and superior engine performance than branched isomers[7]. Additionally, the combination of n-butanol with hydrogen in SI engines can further improve combustion stability and reduce emissions, although it may increase NOx emissions[8]. Challenges such as lower atomization and volatility of n-butanol can be mitigated by optimizing injection strategies, such as increasing injection pressure and adjusting timing, which enhance mixture formation and combustion efficiency[9]. Furthermore, a combined injection approach, involving both port and direct injection of n-butanol, can optimize combustion and emission outcomes, with specific injection ratios yielding the best performance[10]. Overall, butanol's potential as a renewable fuel substitute in SI engines is promising, offering improved combustion characteristics and reduced emissions, although careful consideration of its molecular structure and injection strategies is crucial for maximizing benefits.

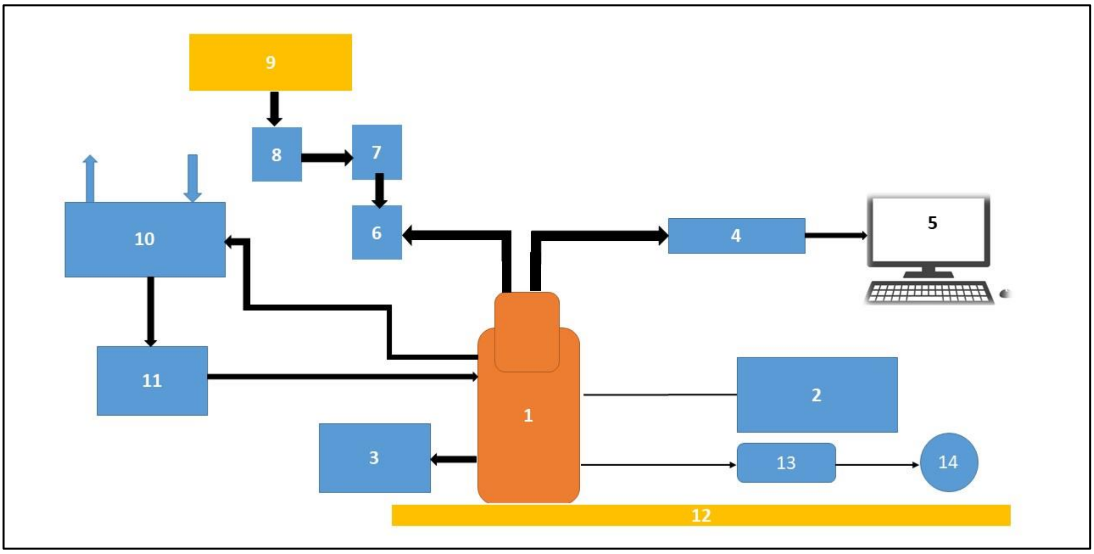
2. Materials and Methods

Experimental Setup

The experimental apparatus in this study consists of a single cylinder, four-stroke SI (Spark Ignition) engine (Honda GX200D QX) with an air-cooled engine of 196 cc displacement and maximum power output of 4.1kW at 3600 rpm. The engine is coupled to an eddy current dynamometer in order to apply variable loads to the engine during testing. The water cooled dynamometer also has a load cell to measure the engine load accurately. The setup is provided with several sensors to record some engine parameters including crank angle, combustion pressure, airflow, fuel flow, and temperature. These signals are sent to a data acquisition system via NI USB-6210 interface for real time performance monitoring and logging. The test bench possesses an air box with an orifice meter and a manometer for airflow measurement. Fuel flow is measured with the use of the differential pressure (DP) transmitter and exhaust gas temperature is measured using Type-K thermocouples. The system also includes a combustion pressure measuring device which is a piezoelectric pressure sensor as well as a measuring device for determining crank angles during operation of the engine. The setup also allows for real-time P-θ and PV diagrams to study the combustion process in detail.

Test Procedure

The experiment was conducted on a single-cylinder, four-stroke, air-cooled gasoline engine (Honda GX200D QX) connected to an eddy current dynamometer for load variation. The engine was tested with pure gasoline (G100) and n-butanol/gasoline blends (B10G90, B20G80, B30G70) under varying loads (25%, 50%, 75%, and 100%). For each fuel blend, the engine was operated at a steady-state condition for each load. Key performance parameters such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and combustion parameters including in-cylinder pressure and heat release rate (HRR) were measured using advanced data acquisition systems. Emission parameters, including carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC), and nitrogen oxides (NOx), were recorded using emission analyzers. Combustion characteristics were captured in the form of pressure-crank angle diagrams and heat release rate curves. Each test was repeated to ensure data consistency, and the system was calibrated as per manufacturer guidelines to ensure accuracy. The results were analyzed to evaluate the impact of n-butanol blending on engine performance and emissions.



1. Engine, 2. Dynamometer 3. Exhaust gas Analyzer 4. Open ECU 5. Computer 6. Intake manifold, 7. Fuel rail 8. Fuel pump, Fuel filter 9. Fuel Reservoir 10. Heat Exchanger 11. Coolant pump, 12. Engine setup bed 13. Oil reservoir 14. Oil pump

Figure 1: Schematic representation of Experimental Setup

Preparation of n-butanol blends

The preparation of n-butanol/gasoline blends involves a systematic process to ensure uniformity and reliability. First, the required equipment, such as clean and calibrated measuring cylinders or volumetric flasks, is set up to accurately measure the components. For each blend, the appropriate volumetric ratio is calculated—10% n-butanol with 90% gasoline for B10G90, 20% n-butanol with 80% gasoline for B20G80, and 30% n-butanol with 70%

gasoline for B30G70. Gasoline is first poured into a clean mixing container, followed by the gradual addition of n-butanol. The mixture is sealed and thoroughly shaken to achieve homogeneity, with visual inspection ensuring no phase separation. The prepared blend is then stored in airtight, labeled containers to prevent contamination or evaporation. Finally, quality assurance checks, such as verifying density and calorific value, are conducted to ensure the blends meet the required standards before being used for engine testing. This careful process guarantees consistent and reliable fuel mixtures for performance evaluation.

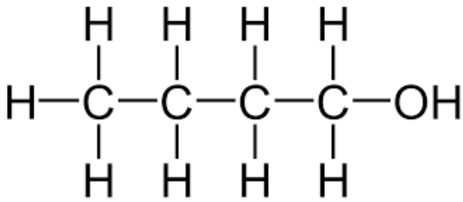


Figure 2: Chemical Structure of n-butanol

Table 1: Properties of Test Fuels

Property	ASTM Standard	Gasoline	n-butanol
Chemical Formula		C_8H_{18}	C_4H_9OH
Calorific Value (MJ/kg)	ASTM D4809	44.0	33.3
Density @ 15ºC (kg/m^3)	ASTM D4052	745	813
Oxygen content (% by mass)	ASTM D5622	0	26.63
Octane Number	ASTM D2699	91-95	118
Latent heat of Vaporization (kJ/kg)	ASTM D2598	305	670
Stoichiometric Air-fuel ratio	ASTM D5291	14.7	11.1
Boiling Point(ºC)	ASTM D86	25-210	97

Table 2: Specifications of the Test Engine

Description	Specifications
Make and Model	Honda GX 200 QX
Power (kW)	4.1
Connecting rod length (mm)	105
Cylinder bore (mm)	68
Stroke length (mm)	54
Number of strokes	4
Type of cooling	Air cooled
Dynamometer	Type eddy current, water cooled with loading unit

Uncertainty Analysis

Estimating uncertainties and errors is a crucial aspect of any experimental investigation. Uncertainties can arise from various sources, including environmental conditions, calibration procedures, observations, instrument selection, and potential reading errors. It is important to analyze and quantify these errors to evaluate the accuracy of the conducted experiments. In this study, the partial differentiation method was employed to determine uncertainties in dependent parameters such as brake power, fuel consumption, and brake thermal efficiency.

The uncertainty percentages of various instruments, as presented in Table 4, were used in these calculations. This method allows for a comprehensive assessment of the uncertainties associated with these parameters. Furthermore, uncertainties in independent parameters were evaluated by conducting a repeated set of 20 readings. The mean, standard deviation, and standard error were calculated based on these readings to determine the uncertainties in these parameters. By considering and quantifying uncertainties and errors, this study ensures a robust analysis of the experimental results, allowing for a more accurate interpretation and assessment of the findings.

To assess the measurement error in the HC, NOx, and CO parameters, the following equation can be employed.

$$q = \sqrt{\frac{\sum_{i=1}^{N}(c_i - c)^2}{N-1}}$$

where c1, c2, c3 . . . are measured values and c is the mean of the measured values. N refers to the number of values measured.

Similarly BP and BSFC can be calculated by the following equation:

$$q = \left[\left(\frac{\partial q}{\partial C_1}\,\Delta c_1\right)^2 + \left(\frac{\partial q}{\partial C_2}\,\Delta c_2\right)^2 + \ldots\ldots\left(\frac{\partial q}{\partial C_n}\,\Delta c_n\right)^2\right]^{\frac{1}{2}}$$

where c_1, c_2, c_3 are the measured values and q depends on c_1, c_2, c_3 . . . c_n, $\frac{\partial q}{\partial C_1}, \frac{\partial q}{\partial C_2}, \ldots\ldots \frac{\partial q}{\partial C_n}$ are partial derivatives of q

Table 3: Uncertainty analysis

S.No	Parameter	Range	Resolution	Measuring principle	Uncertainty %
1	NO_x	0-5000ppm	1 ppm	Chemiluminescence detector	1.51
2	CO	0–9.99%vol.	0.001% vol.	Non dispersive infrared	2.24
3	O_2	0–25% vol.	0.1% vol.	Non dispersive infrared	1.2
4	HC	0–1500 ppm	1 ppm	Flame ionisation detector	2.85
5	CO_2	0–20%vol.	0.01% vol.	Non dispersive infrared	1.23
6	T	0–400°C	1°C	K-type (Chromel/Alumel)	0.8
7	BSFC	0–240 g/kWh	-	-	1.63
8	BP	0–399.856 KW	-	-	1.75

3. Results and Discussions

Brake Thermal Efficiency

The graph 3 illustrates the relationship between Brake Thermal Efficiency (BTE) and engine load for four different fuel blends: G100 (pure gasoline), B10G90 (10% n-butanol and 90% gasoline), B20G80 (20% n-butanol and 80% gasoline), and B30G70 (30% n-butanol and 70% gasoline). As the load increases from 25% to 100%, the BTE rises for all blends, demonstrating improved engine efficiency at higher loads. Among the blends, B20G80 achieves the highest BTE across all loads, followed by B30G70 and B10G90, with G100 exhibiting the lowest efficiency. This trend indicates that the oxygenated nature of n-butanol enhances combustion efficiency, with B20G80 achieving an optimal balance between oxygenation and calorific value. The consistent performance improvement with increasing n-butanol content highlights its potential as a sustainable fuel additive for better engine efficiency.

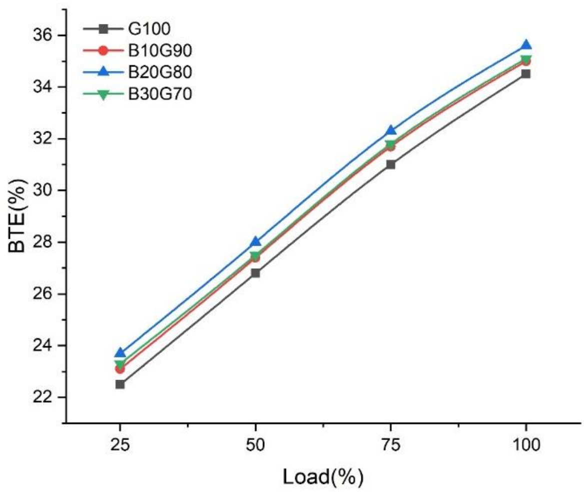


Figure 3: Load vs BTE of n-butanol blends

Brake Specific Fuel Consumption

The figure 4 depicts the variation in Brake Specific Fuel Consumption (BSFC) with respect to engine load for different fuel blends: G100 (pure gasoline), B10G90 (10% n-butanol and 90% gasoline), B20G80 (20% n-butanol and 80% gasoline), and B30G70 (30% n-butanol and 70% gasoline). As the load increases from 25% to 100%, BSFC decreases for all the blends, highlighting improved fuel utilization at higher loads. Among the blends, G100 exhibits the lowest BSFC due to its higher calorific value, while B30G70 shows the highest BSFC across all loads due to the lower energy content of n-butanol. B20G80 achieves better fuel consumption than B30G70 and B10G90, reflecting its balanced oxygenation and calorific value. This trend indicates that while adding n-butanol enhances combustion efficiency, it slightly increases fuel consumption due to its lower energy density compared to pure gasoline.

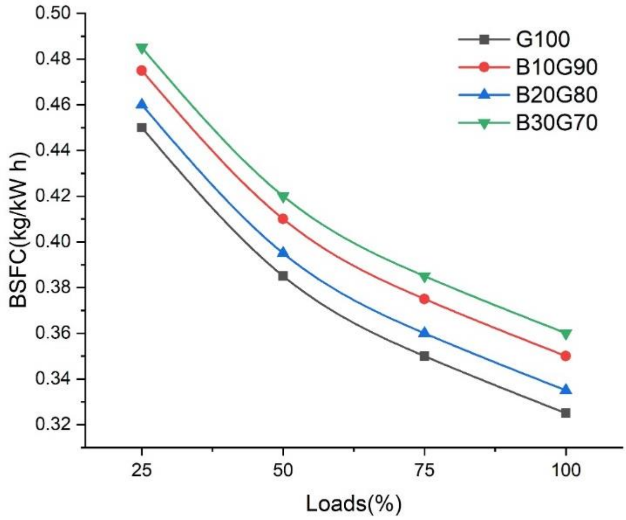


Figure 4: Load vs BSFC with different butanol blends

HC Emissions

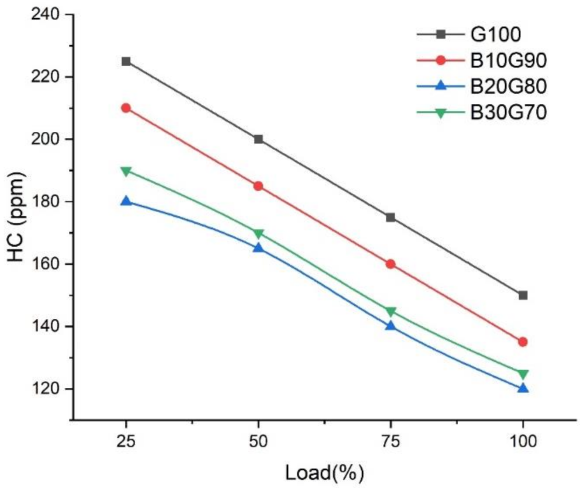


Figure 5: HC emissions vs Load with different butanol blends

The figure 4 depicts the variation in Hydrocarbon (HC) emissions, measured in ppm, with engine load for four fuel blends: G100 (pure gasoline), B10G90 (10% n-butanol and 90% gasoline), B20G80 (20% n-butanol and 80% gasoline), and B30G70 (30% n-butanol and 70% gasoline). As engine load increases from 25% to 100%, HC emissions decrease for all blends due to improved combustion efficiency at higher loads. Among the blends, B20G80 shows the lowest HC emissions across all loads, reflecting its optimal balance of oxygen content and calorific value, which enhances combustion and reduces unburnt hydrocarbons. G100 exhibits the highest HC emissions due to the absence of oxygenated components, while B10G90 and B30G70 follow intermediate trends. This indicates that B20G80 is the most effective blend for minimizing HC emissions while maintaining efficient combustion performance.

CO Emissions

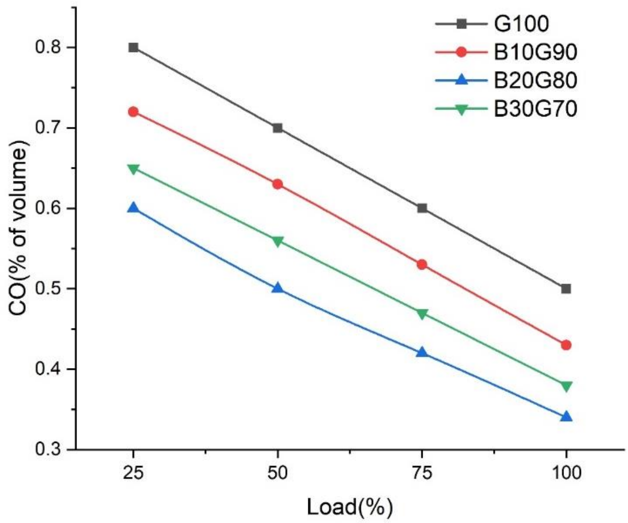


Figure 6: Load vs CO emissions with different butanol blends

The graph 5 represents the variation in Carbon Monoxide (CO) emissions, expressed as a percentage of volume, with respect to engine load for four fuel blends: G100 (pure gasoline), B10G90 (10% n-butanol and 90% gasoline), B20G80 (20% n-butanol and 80% gasoline), and B30G70 (30% n-butanol and 70% gasoline). As the load increases from 25% to 100%, CO emissions decrease for all blends due to enhanced combustion efficiency at higher loads. Among the blends, G100 shows the highest CO emissions across all loads, which can be attributed to incomplete combustion caused by the absence of oxygenated additives. Blends containing n-butanol demonstrate lower CO emissions, with B20G80 achieving the lowest values at most load conditions. The improved performance of n-butanol blends is due to the presence of oxygen in the fuel, which promotes better oxidation and reduces incomplete combustion. This trend highlights the potential of B20G80 as an effective blend for minimizing CO emissions while maintaining combustion performance.

CO_2 Emissions

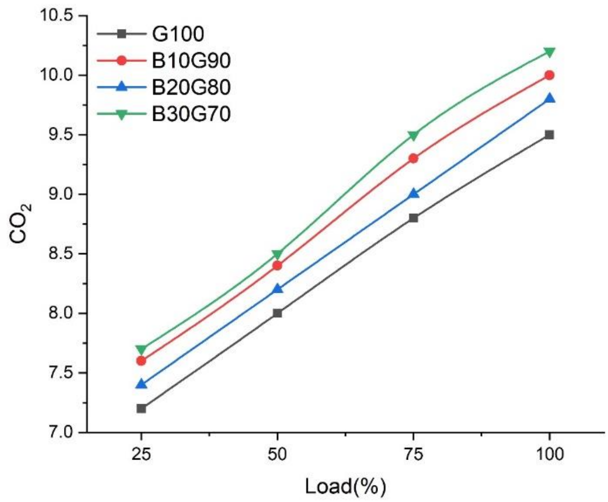


Figure 7: Load vs CO_2 emissions with different butanol blends

The graph 6 shows the variation of Carbon Dioxide (CO_2) emissions, expressed as a percentage of volume, with engine load for four fuel blends: G100 (pure gasoline), B10G90 (10% n-butanol and 90% gasoline), B20G80 (20% n-butanol and 80% gasoline), and B30G70 (30% n-butanol and 70% gasoline). As the engine load increases from 25% to 100%, CO_2 emissions rise for all blends due to more complete combustion at higher loads, which results in a greater proportion of carbon being oxidized into CO_2. Among the blends, B30G70 produces the highest CO_2 emissions across all loads, followed by B10G90 and B20G80, while G100 has the lowest CO_2 emissions. This increase in CO_2 with higher n-butanol content is attributed to improved combustion efficiency facilitated by the oxygenated nature of n-butanol. The trend suggests that n-butanol blends, especially B20G80, enable more efficient combustion, reducing incomplete oxidation but leading to slightly higher CO_2 emissions due to better utilization of carbon in the fuel.

NOx Emissions

The graph 7 represents the variation in Nitrogen Oxides (NOx) emissions, measured in ppm, with engine load for four fuel blends: G100 (pure gasoline), B10G90 (10% n-butanol and 90% gasoline), B20G80 (20% n-butanol and 80% gasoline), and B30G70 (30% n-butanol and 70% gasoline). As the engine load increases from 25% to 100%, NOx emissions rise for all blends. This increase is primarily due to higher combustion temperatures and improved oxygen availability at greater loads, which enhance the formation of NOx. Among the blends, B30G70 shows the highest NOx emissions, followed by B20G80 and B10G90, while G100 has the lowest emissions. The oxygenated nature of n-butanol contributes to better combustion efficiency and higher peak temperatures, leading to increased NOx formation for blends with higher n-butanol content. This trend highlights the trade-off between improved combustion and elevated NOx emissions when using oxygenated fuel blends.

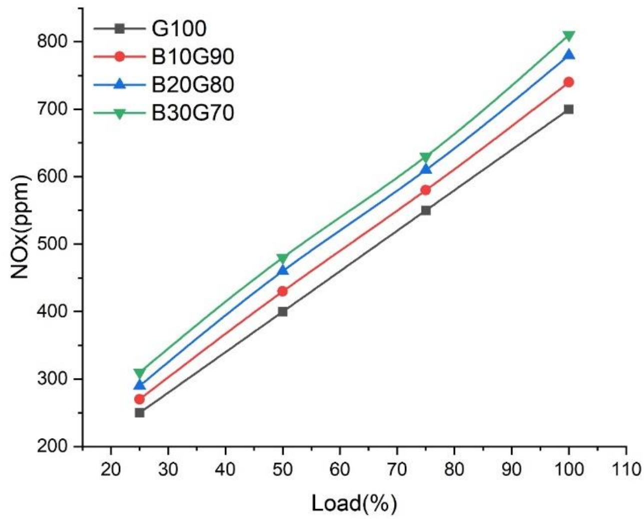


Figure 8: Load vs NOx emissions with different butanol blends

4. Conclusions

The experimental analysis of a gasoline engine using pure gasoline (G100) and n-butanol/gasoline blends (B10G90, B20G80, and B30G70) revealed significant findings across various performance and emission parameters. Brake Thermal Efficiency (BTE) improved with increasing engine load for all fuel blends, with B20G80 demonstrating the highest efficiency, owing to its optimal balance of oxygenation and energy density. Brake Specific Fuel Consumption (BSFC) decreased as load increased, with B20G80 again showing favorable results among the blends. Hydrocarbon (HC) and Carbon Monoxide (CO) emissions reduced with rising engine load due to better combustion efficiency, with B20G80 recording the lowest emissions in both categories. Carbon Dioxide (CO_2) emissions increased as a result of more complete combustion, with B30G70 showing the highest levels due to enhanced oxidation of carbon. Nitrogen Oxides (NOx) emissions also increased with load, with higher n-butanol blends like B30G70 producing the highest levels due to elevated combustion temperatures. Overall, B20G80 emerged as the most effective blend, achieving a balance between high thermal efficiency and low emissions. However, the rise in NOx emissions with higher n-butanol content suggests a need for additional strategies, such as exhaust gas recirculation or after-treatment systems, to mitigate their formation. These results underscore the potential of n-butanol as a promising alternative fuel for spark-ignition engines, providing improved efficiency and reduced harmful emissions.

Disclosure of Interest

We have no conflict of interest to disclose

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