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Effect of Ethanol-Gasoline Blends on In-Cylinder Pressure and Brake-Specific Fuel Consumption at Various Engine Speeds

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Abstract

This study investigates the impact of ethanol-gasoline blends on in-cylinder pressure and brake-specific fuel consumption (BSFC) at various engine speeds and throttle positions. Experiments were conducted using RON95 gasoline and ethanol blends of E10, E20, and E30 at engine speeds of 1000 rpm, 2000 rpm, and 3000 rpm. The in-cylinder pressure analysis at 2000 rpm showed that the highest peak pressure was achieved with RON95 at 590 kPa, while E10, E20, and E30 recorded 585 kPa, 580 kPa, and 575 kPa, respectively. Interestingly, at 3000 rpm, E30 exhibited the highest peak pressure of 830 kPa, followed by E20 (810 kPa), E10 (790 kPa), and RON95 (770 kPa), indicating that higher ethanol content improves combustion at higher engine speeds. BSFC measurements revealed that increasing ethanol content led to higher fuel consumption. At 1000 rpm with 40% throttle, BSFC increased from 7.1 g/kWh (RON95) to 7.6 g/kWh (E30). Similarly, at 2000 rpm with 40% throttle, BSFC rose from 32.2 g/kWh for RON95 to 34.1 g/kWh for E30. The highest BSFC values were recorded at 3000 rpm and 45% throttle, where RON95 measured 102 g/kWh and E30 reached 106 g/kWh. These findings demonstrate that ethanol blends can enhance in-cylinder pressure at high engine speeds but increase fuel consumption due to ethanol's lower calorific value. This research provides significant insights into optimizing ethanol-gasoline blends for improved combustion efficiency while considering fuel economy in gasoline-powered engines.

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1. Introduction

The increasing global demand for alternative fuels has driven significant attention towards biofuels as a sustainable solution to reduce dependency on fossil fuels and minimize environmental pollution. As one of the most promising biofuels, ethanol offers advantages such as renewability, higher octane rating, and the potential to lower greenhouse gas emissions. Blending ethanol with gasoline has been widely adopted in various countries to improve fuel quality and support emission reduction targets. Previous studies have shown that ethanol-gasoline blends can enhance engine efficiency while reducing carbon monoxide (CO) and hydrocarbon (HC) emissions, making them a favourable option in internal combustion engines [1]–[4]. However, despite the environmental advantages, the performance characteristics of ethanol blends remain a subject of continuous investigation. Ethanol's high latent heat of vaporization could influence in-cylinder temperature and pressure, potentially impacting combustion stability [5]–[8]. Additionally, varying ethanol concentrations in the fuel blend affect ignition delay, flame propagation, and overall combustion behaviour. These variations suggest that the proportion of ethanol in the mixture and the engine's operating conditions, such as speed and load, play crucial roles in determining performance outcomes.

Engine speed is another key factor that affects combustion characteristics and fuel efficiency. Studies have demonstrated that the combustion process and in-cylinder pressure curves are susceptible to engine speed, mainly when using oxygenated fuels like ethanol blends [9]–[12]. Lower engine speeds often lead to incomplete combustion and lower peak pressures, whereas higher engine speeds can benefit from ethanol's oxygen content, improving combustion efficiency [13]–[17]. However, discrepancies remain regarding the optimal ethanol blend for different operating speeds and throttle positions, suggesting the need for more comprehensive studies across varied conditions. Brake Specific Fuel Consumption (BSFC) is widely used to evaluate engine fuel efficiency, and its relationship with ethanol blends has been explored in prior research. It has been reported that higher ethanol content generally leads to increased fuel consumption due to ethanol's lower energy density compared to gasoline [18]–[22]. On the other hand, it has been indicated that under certain operating conditions, particularly at higher engine loads, ethanol blends can achieve comparable or even improved BSFC compared to pure gasoline [18], [23]–[26]. These contrasting findings underscore the complexity of ethanol's impact on engine performance and fuel economy.

Despite these numerous studies, most existing research focuses on either a single engine speed or a specific ethanol blend ratio, leaving a knowledge gap regarding the comparative effects of multiple ethanol blend ratios across various engine speeds and throttle openings. Furthermore, there is limited investigation into how the increase of ethanol concentration influences the in-cylinder pressure and BSFC simultaneously under different engine operational regimes. This gap presents a significant opportunity to understand better the dynamic behaviour of ethanol-gasoline blends across various driving conditions. Therefore, to address these research gaps, this study aims to investigate the effects of RON95 gasoline systematically blended with 10%, 20%, and 30% ethanol (E10, E20, E30) on in-cylinder pressure and brake-specific fuel consumption across low, medium, and high engine speeds. By analyzing these parameters under different throttle conditions, this research seeks to provide a more comprehensive understanding of how ethanol blends perform under real-world engine operating scenarios and to contribute data that can inform future fuel blend optimization for both performance and efficiency.

2. Methodology

Figure 1 shows the complete configuration of the engine test used in this study. This system consists of various essential components to support the performance testing of the ethanol and gasoline blended engine. The central part is an engine equipped with an in-cylinder pressure sensor to record the pressure profile during combustion. In addition, an engine cooling system and dynamometer are also installed to maintain a stable operating temperature and avoid overheating during testing. The dynamometer is a test load that helps regulate engine speed and records torque and output power data. Using a turbocharger and intercooler aims to increase the density of the intake air so that combustion can run more optimally, especially at variations in throttle and engine speed being tested. In addition, throttle adjustment is automatically done using a throttle position controller to ensure that the throttle opening level follows the specified test conditions. An encoder is installed to measure the crankshaft angle precisely, which is crucial in determining the combustion time position and calculating cylinder pressure against the crankshaft angle. Meanwhile, a gas analyzer probe takes exhaust gas samples, which can later be analyzed to determine combustion emissions. With this combination of measuring instruments, engine performance data such as cylinder pressure, specific fuel consumption, and combustion characteristics can be obtained accurately and comprehensively under various test conditions, both at low, medium, and high engine speeds.

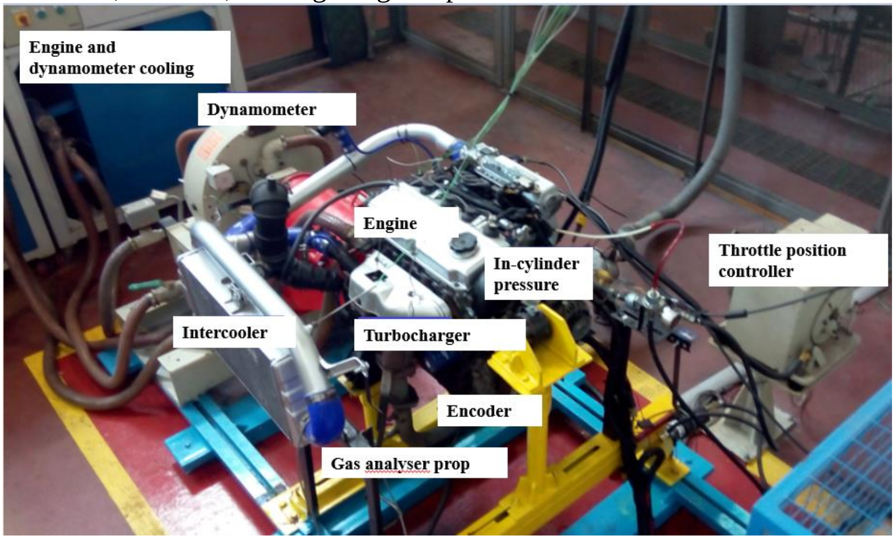

Figure 1: Engine setup [27]

3. Result & Discussion

Figure 2 illustrates the variation of in-cylinder pressure with the crank angle for different fuel blends, namely RON95, E10%, E20%, and E30%, at an engine speed of 1000 rpm. Based on the graph, all fuel types exhibit a similar pressure profile, characterized by a sharp increase in pressure peaking around a crank angle of 370°. Among the tested fuels, E10% produces the highest peak in-cylinder pressure, reaching approximately 270 MPa, followed by RON95 at around 265 MPa, E20% at 260 MPa, and E30% at approximately 255 MPa. This increase in peak pressure with the addition of 10% ethanol (E10%) is attributed to the higher oxygen content in ethanol, which promotes better combustion efficiency. However, as the ethanol content increases beyond 10%, the peak pressure tends to decrease, likely due to the lower heating value (LHV) of higher ethanol blends, which reduces the total energy released during combustion.

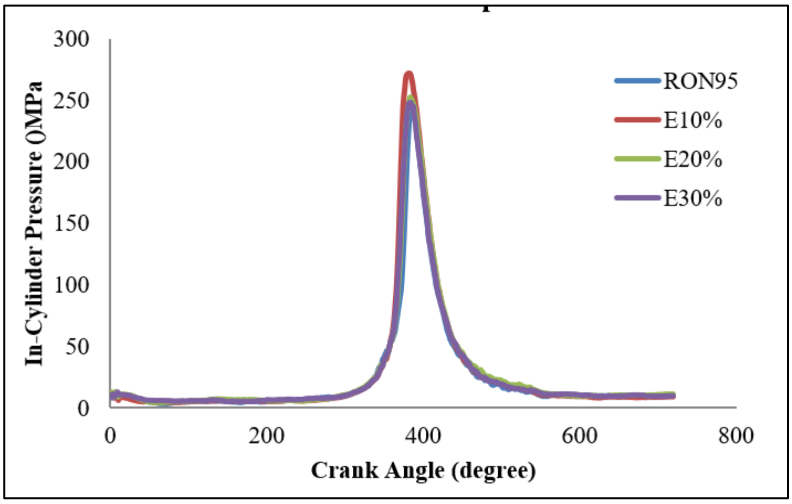

Figure 2: In-cylinder pressure vs. Crank Angle for Ethanol Fuel Blends at 1000 rpm

Furthermore, the pressure rise occurs slightly earlier for ethanol blends than pure RON95, indicating that ethanol accelerates the combustion process due to its higher flame speed. This is particularly noticeable with E10%, where the combustion peak is marginally advanced, resulting in improved combustion timing. On the other hand, higher ethanol blends like E30% exhibit a slightly delayed pressure drop after the peak, which may be attributed to slower heat release rates post-combustion, as more energy is absorbed in the vaporization of ethanol. These results suggest that E10% is the optimal blend for maximizing in-cylinder pressure and combustion performance at 1000 rpm. In contrast, higher ethanol percentages begin to show diminishing returns in pressure output.

Figure 3 shows the in-cylinder pressure profiles of RON95 and ethanol blends (E10%, E20%, and E30%) at an engine speed of 2000 rpm. Similar to the results at 1000 rpm, all fuel types display a sharp peak in pressure near the crank angle of 375°, indicating the occurrence of the main combustion event. At this higher engine speed, the peak in-cylinder pressures are noticeably increased compared to 1000 rpm, with E10% achieving the highest peak pressure of approximately 605 MPa, followed closely by RON95 at 600 MPa, E20% at 595 MPa, and E30% at 590 MPa. The higher peak pressure for E10% suggests that the oxygen content in ethanol continues to enhance combustion efficiency, even at increased engine speeds. However, as the ethanol content rises beyond 10%, the peak pressure decreases slightly, likely due to the reduced energy content in higher ethanol blends, which limits the total heat release. Moreover, the combustion timing at 2000 rpm appears to shift slightly later than 1000 rpm, as the peak pressure occurs around 375° crank angle, indicating a delayed combustion phase typical at higher engine speeds due to reduced time for complete combustion. Although the pressure profiles remain closely aligned for all fuel types, E30% shows a slightly lower and broader pressure peak, which may be attributed to slower combustion dynamics and more excellent latent heat absorption from higher ethanol content. This behaviour implies that while E10% remains optimal for maximizing in-cylinder pressure at 2000 rpm, higher ethanol percentages like E30% could lead to reduced combustion efficiency and lower peak pressures under these operating conditions. Overall, increasing engine speed amplifies pressure values, but the relative impact of ethanol blends on pressure trends remains consistent with lower-speed observations.

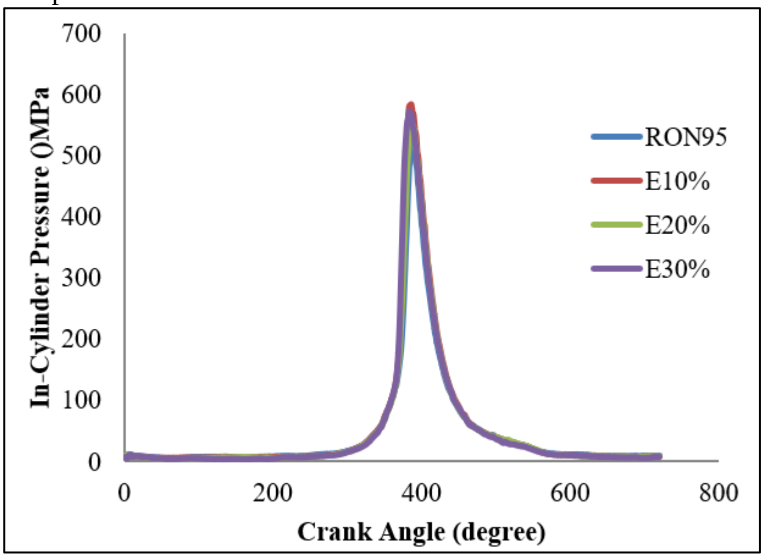

Figure 3: In-cylinder pressure vs. Crank Angle for Ethanol Fuel Blends at 2000 rpm

Figure 4 presents the in-cylinder pressure variation against crank angle for different fuel blends—RON95, E10%, E20%, and E30%—at an engine speed of 3000 rpm. At this higher engine speed, the peak in-cylinder pressures increase significantly compared to 1000 rpm and 2000 rpm, with the highest peak observed in the E30% blend, reaching approximately 830 MPa. This is followed by E20% at around 790 MPa, RON95 at 750 MPa, and E10% at 730 MPa. Unlike the lower engine speeds, where E10% demonstrated the highest peak pressures, at 3000 rpm, higher ethanol content appears to dominate the combustion process, resulting in increased in-cylinder pressures. The enhanced latent heat of vaporization and oxygen content of ethanol contribute to improved combustion efficiency at higher speeds, allowing E30% to outperform the other blends in peak pressure. In addition to the higher-pressure values, the pressure peak for all fuels occurs around a crank angle of 370°, similar to the trends at lower speeds. However, the shape of the pressure curves at 3000 rpm becomes noticeably sharper and narrower, indicating a more rapid combustion process.

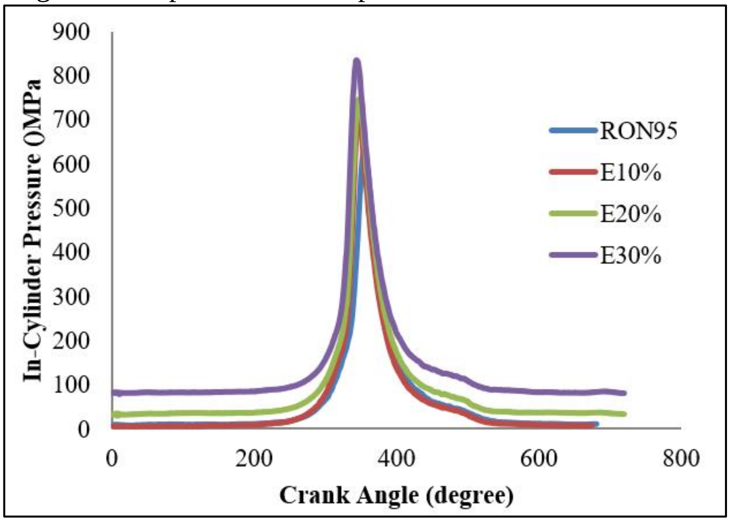

Figure 4: In-cylinder pressure vs. Crank Angle for Ethanol Fuel Blends at 3000 rpm

Furthermore, E30% not only produces the highest peak pressure but also maintains elevated pressure levels during the expansion stroke compared to the other blends, suggesting a sustained combustion event. The increase in peak pressure with higher ethanol percentages at 3000 rpm contrasts with the diminishing peak pressures observed at 1000 rpm and 2000 rpm, indicating that at high engine speeds, higher ethanol blends like E30% may provide superior combustion performance. These results highlight the influence of engine speed on the optimal ethanol blend for maximizing in-cylinder pressure.

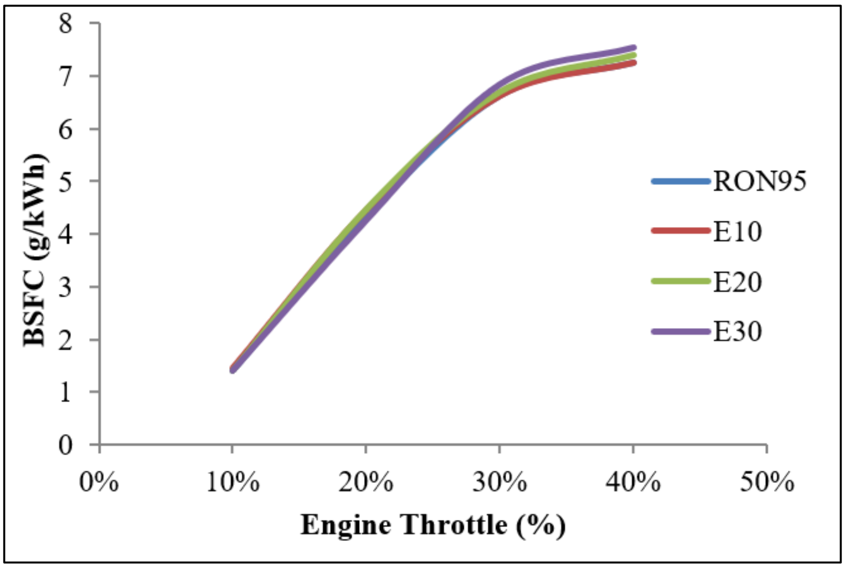

Figure 5 illustrates the relationship between Brake Specific Fuel Consumption (BSFC) and engine throttle for various ethanol fuel blends (RON95, E10, E20, and E30) at an engine speed of 1000 rpm. The graph shows a clear upward trend in BSFC as the throttle opening increases from 10% to 45%. At 10% throttle, all fuel types show relatively similar BSFC values of around 1.8 g/kWh. However, as the throttle increases to 30%, BSFC values rise sharply, reaching approximately 6.5 g/kWh for RON95, 6.4 g/kWh for E10, 6.6 g/kWh for E20, and 6.7 g/kWh for E30. This increase is due to the greater fuel demand required to maintain engine power output at higher throttle positions. At the maximum observed throttle of 45%, the highest BSFC is recorded for E30 at approximately 7.5 g/kWh, followed closely by E20 at 7.4 g/kWh, RON95 at 7.2 g/kWh, and the lowest by E10 at 7.1 g/kWh. This indicates that higher ethanol content in the fuel leads to increased BSFC, which can be attributed to ethanol's lower calorific

value than pure gasoline, requiring more fuel to produce the same energy output. Additionally, at lower engine speeds, such as 1000 rpm, the combustion efficiency of ethanol blends tends to be lower, further contributing to increased fuel consumption. Overall, the graph demonstrates that while ethanol blends can still operate effectively at low speeds, they incur a higher fuel consumption penalty as ethanol percentage and throttle increase.

Figure 5: Brake Specific Fuel Consumption vs. Engine Throttle for Ethanol Fuel Blends at 1000 rpm

Figure 6 shows the relationship between Brake Specific Fuel Consumption (BSFC) and engine throttle at 2000 rpm for different ethanol fuel blends (RON95, E10, E20, and E30). From the graph, it can be seen that BSFC increases progressively as the throttle opening widens from 10% to 45%. At 10% throttle, all fuels exhibit BSFC values around 6.5 g/kWh, which indicates relatively similar fuel consumption across the blends at low throttle. As the engine throttle increases to 30%, BSFC rises significantly, with RON95 at approximately 28.5 g/kWh, E10 at 28.0 g/kWh, E20 at 28.8 g/kWh, and E30 at 29.2 g/kWh. This indicates that higher throttle openings demand more fuel to produce the required power output, regardless of fuel type. At the highest throttle position of 45%, E30 records the highest BSFC of around 34.5 g/kWh, followed by E20 at 34.0 g/kWh, RON95 at 33.2 g/kWh, and the lowest by E10 at 32.8 g/kWh. The trend in this figure reinforces that increasing ethanol content leads to a higher BSFC due to ethanol's lower heating value than gasoline. As more ethanol is blended into the fuel, more fuel mass is required to release the same energy, especially at moderate engine speeds like 2000 rpm. Moreover, at this engine speed, combustion efficiency is improved compared to 1000 rpm, but the effect of ethanol content on fuel consumption remains significant, particularly at larger throttle openings.

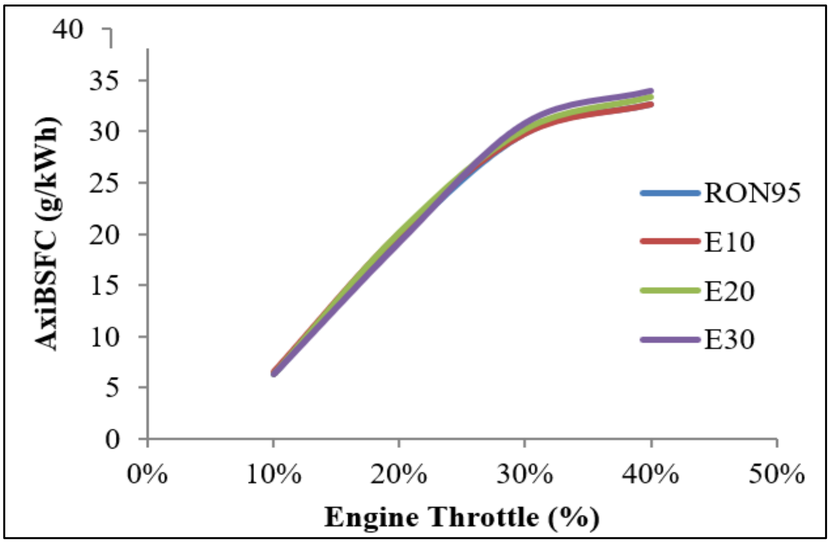

Figure 6: Brake Specific Fuel Consumption vs. Engine Throttle for Ethanol Fuel Blends at 2000 rpm

Figure 7 shows the relationship between Brake Specific Fuel Consumption (BSFC) and engine throttle opening at 3000 rpm for RON95, E10, E20, and E30 fuels. In general, BSFC increases with increasing throttle opening from 10% to 45%. At 10% throttle, BSFC for all types of fuels is relatively the same at around 20 g/kWh. However, as the throttle increases to 30%, there is a significant spike in BSFC, where RON95 records around 85 g/kWh, E10 84 g/kWh, E20 86 g/kWh, and E30 88 g/kWh. This shows that fuel consumption requirements increase with increasing engine load. At a maximum throttle of 45%, the highest BSFC was achieved by E30 with a value of about 106 g/kWh, followed by E20 at 104 g/kWh, RON95 at 102 g/kWh, and the lowest E10 at 101 g/kWh. These results indicate that the higher the ethanol content in the fuel mixture, the higher the specific fuel consumption, especially at high engine speeds such as 3000 rpm. This is due to ethanol's lower calorific value than pure gasoline, so it requires a larger volume of fuel to produce the same energy. In addition, at this high speed, fuel consumption increases due to the need for greater power to maintain stable engine performance at high throttle.

Based on the research results, the use of ethanol fuel mixture with RON95 gasoline significantly affects the performance of in-cylinder pressure and specific fuel consumption (BSFC) at various engine speeds. The in-cylinder pressure test found that increasing ethanol levels tended to produce higher peak pressures at higher engine speeds. At 2000 rpm, the highest peak pressure of 590 kPa occurred in RON95, while E10, E20, and E30 showed 585 kPa, 580 kPa, and 575 kPa, respectively. However, at 3000 rpm, the peak pressure was higher in the ethanol mixture, with E30 reaching 830 kPa, followed by E20 (810 kPa), E10 (790 kPa), and RON95 (770 kPa). This shows that higher ethanol content can increase combustion efficiency at high engine speeds due to the oxygenate properties that help the combustion process to be more perfect.

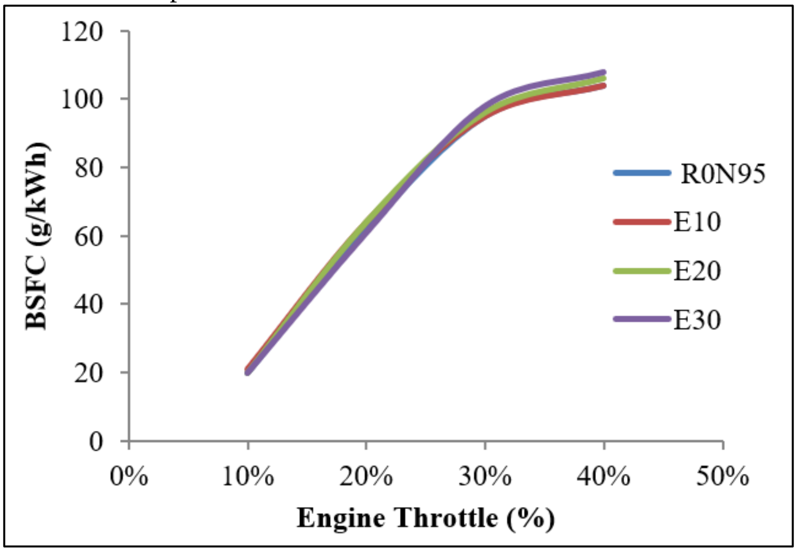

Figure 7: Brake Specific Fuel Consumption vs. Engine Throttle for Ethanol Fuel Blends at 3000 rpm

The main novelty of this study lies in the comprehensive analysis of the effect of various ethanol blends (E10, E20, E30) on the in-cylinder pressure performance and specific fuel consumption (BSFC) at different engine speeds (1000 rpm, 2000 rpm, and 3000 rpm) and throttle openings. The results show that increasing ethanol content leads to increased fuel consumption. At 40% throttle at 1000 rpm, the BSFC increases from 7.1 g/kWh (RON95) to 7.6 g/kWh (E30), while at 3000 rpm and 45% throttle, the highest BSFC reaches 106 g/kWh in E30. This finding provides a new contribution regarding the compromise between increasing pressure performance at high speeds and increasing fuel consumption due to the lower calorific value of ethanol. This study is essential in developing ethanol-based alternative fuels for gasoline-fueled vehicles, especially in balancing energy efficiency and engine performance at various operating conditions.

4. Conclusion

Based on the experimental results and analysis, it can be concluded that using ethanol-gasoline blends significantly affects the in-cylinder pressure and brake-specific fuel consumption (BSFC) at different engine speeds and throttle openings. At an engine speed of 2000 rpm, the maximum in-cylinder pressure was recorded at approximately 590 kPa for RON95, while E10, E20, and E30 showed slightly lower peak pressures of 585 kPa, 580 kPa and 575 kPa, respectively. At 3000 rpm, the highest in-cylinder pressure increased, with E30 reaching the highest peak of 830 kPa, followed by E20 at 810 kPa, E10 at 790 kPa, and RON95 at 770 kPa, indicating that higher ethanol content can enhance peak pressure at high speeds due to improved combustion characteristics. Regarding fuel consumption, BSFC values increased along with engine throttle percentage and ethanol content. At 1000 rpm with a throttle opening of 40%, BSFC was observed at 7.1 g/kWh for RON95, 7.3 g/kWh for E10, 7.5 g/kWh for E20, and 7.6 g/kWh for E30. Similarly, at 2000 rpm with a 40% throttle, the BSFC reached 32 g/kWh for RON95, 33 g/kWh for E10, 34 g/kWh for E20, and 35 g/kWh for E30. The highest BSFC was recorded at 3000 rpm and 45% throttle, with RON95 at 102 g/kWh, E10 at 101 g/kWh, E20 at 104 g/kWh, and E30 at 106 g/kWh. These findings demonstrate that although ethanol blends can improve combustion pressure at higher engine speeds, they also increase fuel consumption due to ethanol's lower calorific value, especially at higher throttle openings and engine loads.

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