Investigating the Correlation Equations and the Impact of Peak Pressure on the Performance and Emissions of an Ethanol Engine

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Received: 27 February 2025 | Revised: 6 April 2025 | Accepted: 19 April 2025

 DOI: https://doi.org/10.48084/etasr.10739

ABSTRACT

The transition from fossil fuels to renewable energy sources is imperative for sustainable development, with ethanol emerging as a promising biofuel due to its potential to reduce harmful emissions. This study investigates the impact of peak pressure (P_{max}) on the performance and emissions of ethanol-fueled internal combustion engines. Simulation results indicate that as P_{max} increases from 24.45 bar to 87.66 bar, torque rises from 12.62 Nm to 24.86 Nm, representing a 97.0% improvement, while Brake-Specific Fuel Consumption (BSFC) drops by 64.78%. However, when P_{max} exceeds 87.66 bar, performance gains become marginal, and fuel efficiency deteriorates. Notably, NO_x emissions increase exponentially with higher P_{max}, rising from 0.000987 g/kWh at 24.45 bar to 9.65 g/kWh at 99.22 bar, underscoring the trade-off between performance and environmental impact. Conversely, CO and HC emissions decrease significantly within the optimal pressure range (59.56–99.22 bar), reaching their lowest values at 87.66 bar before slightly rebounding due to incomplete combustion at extreme pressures. By establishing a quantitative correlation between P_{max}, engine performance, and emissions, this study identifies 87.66 bar as the optimal peak pressure for balancing power output and emissions control in ethanol-fueled engines. These findings provide valuable insights for optimizing ethanol combustion strategies, contributing to the sustainable development of biofuels in the internal combustion engine industry.

Keywords-ethanol fuel; peak pressure; engine performance; emissions

I. INTRODUCTION

The reduction of the dependence on fossil fuels has become an urgent need, with the use of alternative fuels emerging as a prominent trend. Ethanol, an environmentally friendly biofuel, is considered a promising solution to address emission-related pollution. The application of ethanol as an engine fuel has attracted significant research interest, primarily focusing on its performance and impact on emissions [1, 2]. Authors in [3] evaluated the potential of ethanol as an alternative fuel in Compression Ignition (CI) engines, particularly in combination with diesel. The results showed that diesel fumigation methods helped reduce Particulate Matter (PM) and NO_x emissions, confirming ethanol as one of the most effective alternative fuel options. Authors in [4] demonstrated that ethanol significantly reduces harmful emissions (NO_x by 17.3%, CO by 13.1%, and HC by 8.8%), but at the cost of a 3.5–7.1% decrease in brake power and a 6.1–16.8% increase in fuel consumption. To enhance the efficiency of ethanol-fueled engines, authors in [5] experimented with adding 0–6% hydrogen (H_2) in lean-burn conditions. Their findings revealed that with a 6% H_2 addition, power output and energy conversion efficiency remained stable, whereas other levels of H_2 addition had negligible effects. Regarding emissions, introducing 2% H_2 in excess air conditions (10–30%) significantly reduced CO and HC without notably affecting NO_x levels. Beyond the development of alternative fuels, many studies have also integrated advanced technologies to optimize both power output and emissions. Authors in [6] implemented the Turbulent Jet Ignition Method (TJIM) in ethanol engines to enhance combustion chamber turbulence, leading to improved combustion efficiency. Their results showed an increase of 0.42 kW in power output and a 40% reduction in CO emissions. However, NO_x emissions rose by an average of 130%, presenting challenges for emission control. Similarly, authors in [7] combined ethanol fuel with advanced technology by employing artificial neural networks to predict emissions and evaluate engine performance. Their research applied thermal barrier coatings to pistons and utilized gasoline-ethanol blends, revealing that adding 10% ethanol reduced HC by 19% and NO_x by 13%. When the ethanol proportion increased to 20%, performance improvements became even more significant compared to conventional engines.

The above mentioned studies indicate that optimizing ethanol fuel, in conjunction with advanced technologies, not only enhances engine performance, but also mitigates environmental impact, paving the way for more sustainable internal combustion engine development. By synthesizing and analyzing previous studies on ethanol as an alternative fuel for internal combustion engines, this research presents a novel approach by establishing a quantitative correlation equation between peak pressure (P_{max}), engine performance, and emissions. While previous studies primarily focused on the impact of ethanol on either performance or emissions, this study adopts a comprehensive approach, clarifying the relationship between P_{max}, power output, and emissions. Additionally, it identifies an optimal pressure range that enhances engine efficiency without significantly increasing NO_x emissions. Furthermore, this research provides practical insights for optimizing ethanol-fueled engines, contributing to the sustainable development of biofuels in the internal combustion engine industry.

II. SIMULATION MODEL SETUP AND MODEL VALIDATION

The AVL-Boost simulation software is widely recognized for its applications in internal combustion engine research. It enables the modeling of various engine types, including Spark-Ignition (SI) engines and CI engines [8, 9], turbocharged diesel engines, and engines utilizing alternative fuels [10]. Figure 1 illustrates the simulation model developed for the ethanol-fueled engine in this study.

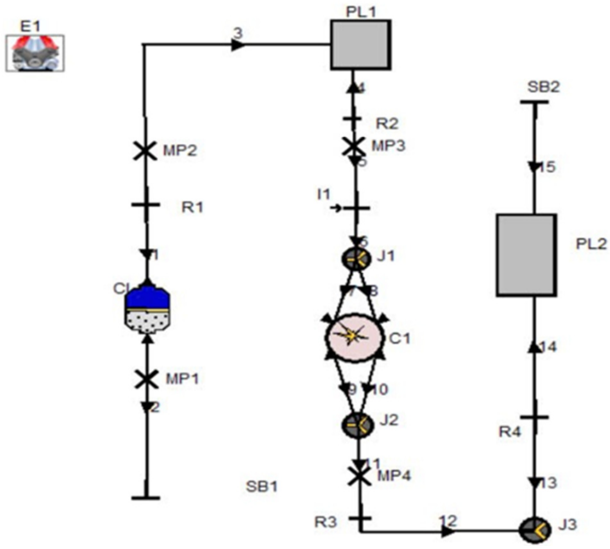

Fig. 1. Schematic diagram of the small SI engine test system. E1: Engine, SB1-2: The dynamo test system, CL1: Air cleaner. PL1-2: Plenum. R1-2-3-4: Restriction elements. I1: Injector. C1: Cylinder. MP1-2-3-4: Measurements of elements. J1-2-3: Junctions elements.

The studied engine is an SI engine featuring a twin-cylinder configuration. It has a compression ratio of 11.8:1, with each cylinder measuring 57 mm in diameter and a stroke length of 53.5 mm. The engine is equipped with a 107.9 mm connecting rod and utilizes a dual-valve system for both intake and exhaust, comprising two intake valves and two exhaust valves in total. The simulation was conducted at full load, an ignition timing of 30 degrees Before Top Dead Center (BTDC), and an air-fuel ratio of 13.6. The environmental temperature was maintained between 29.5 °C and 30 °C. Airflow was used for cooling, the lubricant oil temperature was kept at 80 °C. The simulation results of Figure 2 closely match the experimental data, validating the model's accuracy and reliability. Key parameters like NO_x emissions, ignition timing, engine torque, and peak pressure are strongly correlated between the datasets. While air-mass shows a deviation of less than 5%, the model's predictive capability remains reliable, making it suitable for studying the effects of peak pressure on ethanol engine performance and emissions.

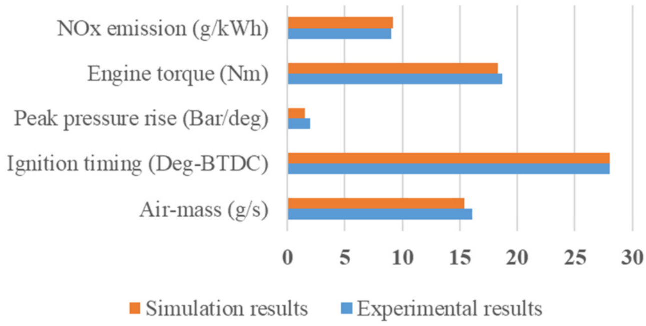

Fig. 2. Model validation.

III. RESULTS AND DISCUSSION

A. The impact of Peak Pressure on Engine Performance

Figure 3 illustrates the relationship between peak pressure and engine torque. Initially, as peak pressure increases from 24.45 bar to 38.72 bar, torque rises from 12.62 Nm to 17.95 Nm, representing a 42.2% increase. This phase exhibits rapid growth, where pressure has a pronounced positive effect on engine performance. When the pressure reaches 59.56 bar, torque continues to increase to 22.93 Nm, demonstrating a linear relationship between pressure increase and engine performance in this stage. The total torque gain compared to the initial value is 81.7%, indicating that higher pressure enhances engine efficiency. As the pressure further increases to 87.66 bar, torque experiences only a slight increase, peaking at 24.86 Nm. This is considered the optimal point, where the engine achieves maximum performance in terms of load capacity and acceleration. However, when the pressure rises to 99.22 bar, torque decreases to 22.87 Nm, reflecting an 8% reduction from the peak value. This phenomenon may result from mechanical losses, overheating, or excessive stress on engine components, ultimately leading to a decline in overall efficiency. Analysis of the results suggests that 87.66 bar is the optimal pressure for achieving the highest torque, while the range of 59.56 – 99.22 bar ensures stable torque output. To accurately describe this relationship, the study has developed an optimal torque characteristic equation as a function of peak pressure:

$$Torque = -0.00607P_{max}{}^2 + 0.96265P_{max} - 12.86459$$

This equation accurately reflects the torque trend within the optimal range, allowing for the adjustment of P_{max} within 59.56 – 99.22 bar to optimize engine performance.

Figure 4 illustrates the relationship between P_{max} in the combustion chamber and the Indicated Mean Effective Pressure (IMEP) of an ethanol-fueled engine. The study results indicate that as peak pressure increases from 24.45 bar to 99.22 bar, IMEP rises from 5.9829 bar to a peak of 11.5727 bar, corresponding to a 93.45% increase. This demonstrates that higher P_{max} leads to more efficient combustion, allowing the engine to generate greater work output. Notably, ethanol, with its high octane rating, can withstand high pressures before auto-ignition, enabling combustion at elevated pressures and thus enhancing thermal efficiency and engine power. However, when P_{max} exceeds the optimal threshold (above 99.22 bar), IMEP starts to decline slightly to 10.662 bar, to a 7.87% reduction. This may be attributed to excessive temperature and pressure in the combustion chamber, leading to uneven combustion, heat losses, and reduced power transmission efficiency. Moreover, excessive pressure can place significant stress on engine components, diminishing the overall efficiency of the combustion process. The analysis suggests that the optimal pressure range for IMEP lies between 59.56 and 99.22 bar. Based on this range, the optimal IMEP characteristic equation as a function of Pmax is formulated as a quadratic function:

$$IMEP = -0.00278P_{max}{}^2 + 0.44025P_{max} - 5.67792$$

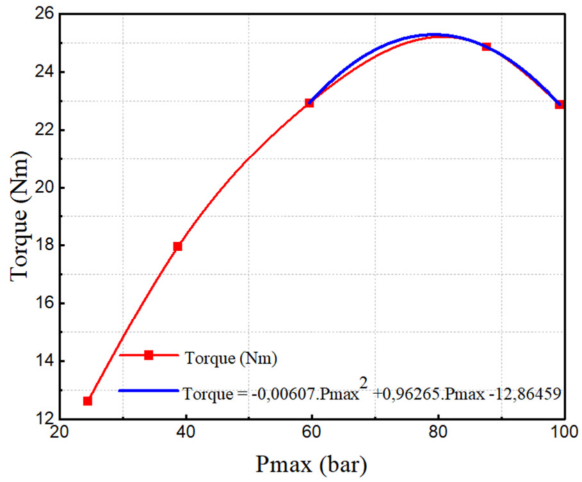

Fig. 3. Influence of P_{max} on engine torque.

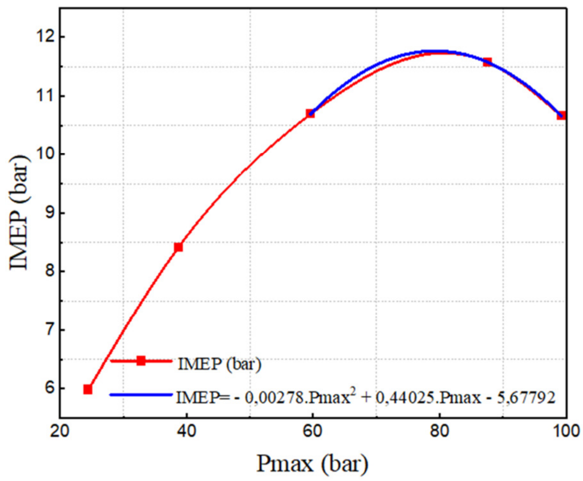

Fig. 4. The impact of P_{max} on IMEP.

Similar to IMEP, maintaining high Brake Mean Effective Pressure (BMEP) is crucial for optimal engine performance, fuel efficiency, and competitive design. Figure 5 shows that as P_{max} increases from 24.45 to 38.72 bar, BMEP rises sharply by 86.3% (from 2.8276 to 5.2666 bar). A further rise to 59.56 bar boosts BMEP to 7.5438 bar (up 43.3%), indicating continued performance gains. At 87.66 bar, BMEP peaks at 8.4291 bar, with a modest 11.7% increase—signaling the optimal pressure for ethanol-fueled performance. However, beyond this point, BMEP declines to 7.5174 bar at 99.22 bar (a 10.8% drop), suggesting reduced efficiency. The optimal pressure range is 59.56–99.22 bar, with a peak at 87.66 bar, consistent with IMEP trends. This relationship is modeled by:

$$\text{BMEP} = -0.00278P_{max}^{2} + 0.44121P_{max} - 8.86256$$

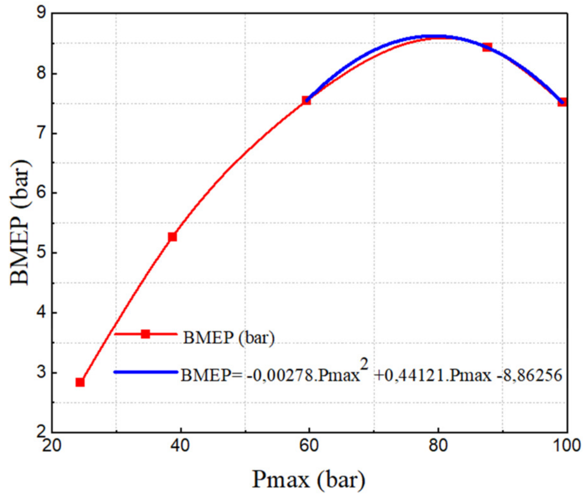

Fig. 5. The impact of P_{max} on BMEP.

Figure 6 clearly illustrates the impact of peak pressure on the Indicated Specific Fuel Consumption (ISFC). Specifically, as peak pressure increases from 24.45 bar to 87.66 bar, ISFC decreases from 843.972 g/kWh to 449.861 g/kWh, representing a 46.68% reduction. Notably, the most significant drop occurs within the range of 24.45 bar to 38.72 bar, with a decrease of 26.79%. This indicates that an increase in peak pressure significantly enhances the efficiency of indicated fuel combustion, as the combustion process becomes faster and more efficient. However, when the peak pressure continues to rise from 87.66 bar to 99.22 bar, ISFC exhibits a slight upward trend, reaching 485.6169 g/kWh (an increase of 7.94%). This phenomenon may result from excessive pressure leading to mechanical losses or a reduction in thermodynamic efficiency due to uneven combustion.

Figure 7 illustrates that as P_{max} increases from 24.45 bar to 87.66 bar, Brake-Specific Fuel Consumption (BSFC) decreases significantly from 1724.47 g/kWh to 607.30 g/kWh, corresponding to a 64.78% reduction. Notably, the most substantial decrease occurs in the range of 24.45 bar to 38.72 bar, reaching 44.11%. This indicates that increasing P_{max} has a positive impact on BSFC, following a similar trend observed with ISFC. However, when P_{max} continues to rise from 87.66 bar to 99.22 bar, BSFC slightly increases to 676.19 g/kWh (an 11.34% rise), suggesting that surpassing an optimal threshold leads to a decline in fuel efficiency. The analysis confirms that peak pressure significantly influences fuel consumption, both in terms of indicated (ISFC) and brake (BSFC) specific fuel consumption. Within the range of 24.45 bar to 87.66 bar, both parameters decrease sharply, demonstrating a considerable improvement in engine efficiency as peak pressure increases. When P_{max} exceeds 87.66 bar, fuel efficiency shows signs of deterioration, as indicated by the slight rise in both ISFC and BSFC. Therefore, 87.66 bar is identified as the optimal peak pressure value for maximizing fuel efficiency in ethanol-fueled engines. Overall, the pressure range of 59.56 bar to 99.22 bar is where ISFC and BSFC remain at their lowest and most stable levels. Based on regression analysis, the optimal characteristic equations for ISFC and BSFC can be determined within the pressure range of 59.56 - 99.22 bar, with a minimum value at P_{max} = 87.66 bar. The optimal characteristic curves of ISFC and BSFC as functions of peak pressure are expressed as follows:

$$\text{ISFC} = 0.11299\,P_{max}^{2} - 18.02267\,P_{max} + 1161.47519$$

$$\text{BSFC} = 0.021552\,P_{max}^{2} - 34.31681\,P_{max} + 1959.42977$$

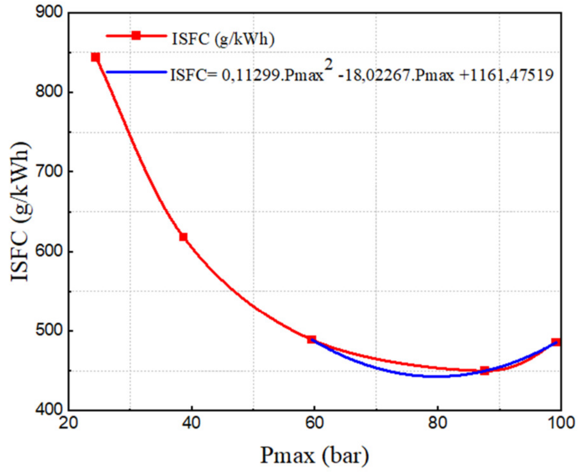

Fig. 6. The impact of P_{max} on ISFC.

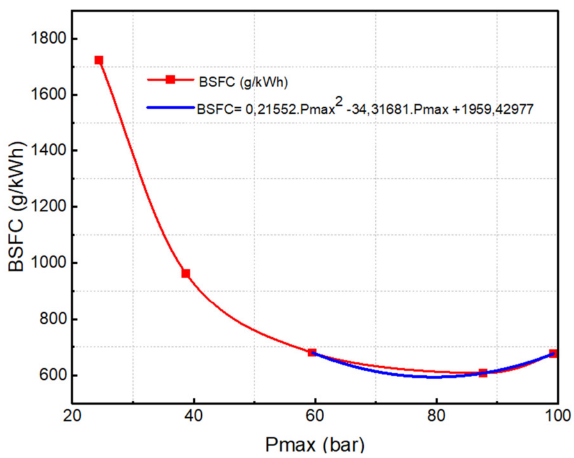

Fig. 7. The impact of P_{max} on BSFC.

B. The Impact of Peak Pressure on Engine Emissions

Figure 8 shows that as P_{max} increases, combustion temperature rises, strongly promoting NO_x formation. When pressure rises from 24.45 bar to 38.72 bar, NO_x emissions increase by 929.8%, and at 59.56 bar, they further rise by 3,757.7%, although the absolute level remains low. However, beyond 60 bar, NO_x emissions surge, peaking at 99.22 bar with 9.65 g/kWh, indicating high sensitivity to pressure and temperature. In contrast, CO and HC emissions tend to decrease with increasing pressure due to more complete combustion.

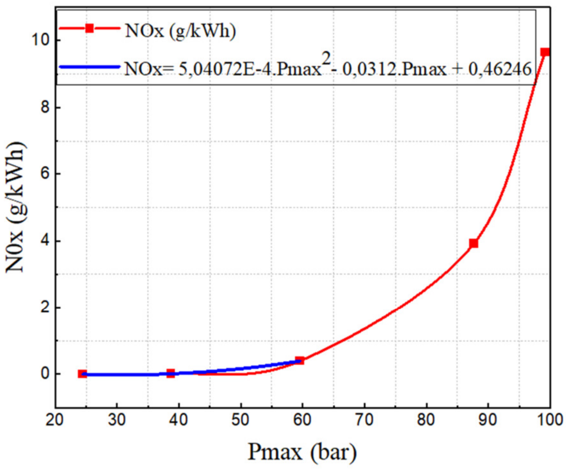

Fig. 8. The impact of P_{max} on NO_x.

As shown in Figure 9, CO drops from 814.652 g/kWh at 24.45 bar to 156.220 g/kWh at 87.66 bar, a reduction of 80.8%. However, in the final stage (87.66–99.22 bar), CO slightly rises to 190.119 g/kWh (a 21.7% increase), likely due to oxygen deficiency and incomplete combustion. Similarly, Figure 10 shows the HC emissions decreasing from 9.7 to 6.5 g/kWh as pressure increases to 59.56 bar, then rising again to 8.35 g/kWh at 99.22 bar, possibly due to the cold flame regions or oxygen-lean mixtures. Overall, NO_x formation is mainly driven by high temperatures, while CO and HC are more influenced by combustion efficiency—improving at moderate pressures but deteriorating slightly at excessive pressures due to oxygen depletion. In summary, each emission type has an optimal pressure range: NO_x decreases within 24.45 – 59.56 bar, CO remains at its lowest levels within 59.56 – 99.22 bar, and HC reaches its optimal range between 38.72 – 87.66 bar. The optimal characteristic equations for each respective range are as follows:

$$NO_x = 5.04072E-4P_{max}^2 - 0.0312P_{max} + 0.46246$$
$$CO = 0.10923P_{max}^2 - 17.48081P_{max} + 849.22199$$
$$HC = 9.67584E-4P_{max}^2 - 0.12377P_{max} + 10.48589$$

Overall, the pressure range of 59.56–99.22 bar can be considered optimal, as CO and HC emissions remain significantly low, although NO_x levels remain relatively high. However, in general, maintaining pressure within this range still contributes significantly to reducing the engine's overall emissions.

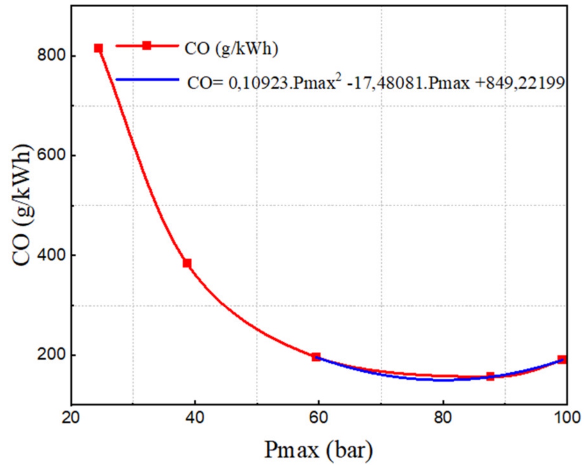

Fig. 9. The impact of P_{max} on CO.

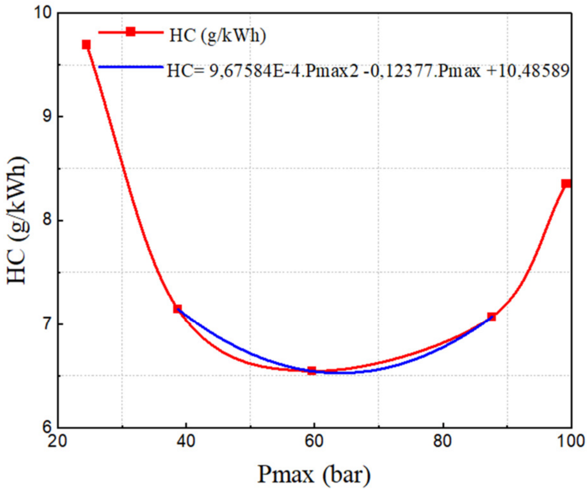

Fig. 10. The impact of P_{max} on HC.

IV. CONCLUSION

This study quantitatively analyzed the relationship between peak pressure (P_{max}), engine performance, and emissions in ethanol-fueled spark-ignition engines using a validated simulation model. The findings reveal that increasing P_{max} significantly improves engine performance indicators such as torque, IMEP, BMEP, and fuel efficiency (ISFC and BSFC), especially within the optimal pressure range of 59.56–99.22 bar. At P_{max} = 87.66 bar, the engine achieves its peak torque and lowest fuel consumption, representing the most efficient operating point. In terms of emissions, higher P_{max} results in increased NO_x emissions due to elevated combustion temperatures, while CO and HC emissions decrease as combustion becomes more complete. However, beyond certain thresholds, CO and HC levels slightly rise again due to oxygen deficiency and uneven combustion. The study established distinct optimal pressure ranges for each emission type and formulated regression equations that express the quantitative correlation between P_{max} and each parameter. These equations provide a novel contribution, offering a predictive tool for engine calibration. Unlike previous studies that often considered performance and emissions in isolation, this research adopts an integrated approach, identifying a pressure range that optimizes both performance and environmental impact. The insights gained serve as a scientific basis for ethanol engine optimization and support the broader effort toward cleaner and more efficient internal combustion engines fueled by bioethanol.

Future research may extend this work by integrating advanced control technologies or hybrid systems to further reduce NO_x emissions while maintaining high engine efficiency.

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