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Impact of Fuel Injection Pressure and Timing on the Performance and Emissions of a Low Heat Rejection CI Engine with Fish Oil Methyl Ester, DEE and Butanol Blend

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study examines how different fuel injection pressures and timings affect the performance and emissions of a Low Heat Rejection (LHR) engine running on blends of fish oil methyl ester, diethyl ether, and butanol. Results indicate that optimizing the injection pressure up to 230 bar enhances engine performance, fuel efficiency, and emission control. Research supports that increasing fuel injection pressure improves performance and combustion characteristics. For instance, studies

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have shown that high injection pressures can reduce NO_X and soot emissions without compromising fuel economy. The depletion of petroleum resources, rising car use, and environmental concerns have made the demand for alternate fuels more urgent. Fish oil methyl ester, which is made from fish oil and may be made from animal fats and edible and non-edible oils, offers a possible substitute for biodiesel. Diesel engines are prized for their effectiveness, dependability, and longevity; timing and fuel injection pressure have a big impact on emissions and performance. However, higher pressures show diminishing benefits, and fine-tuning the injection timing to 29° before top dead centre further improves efficiency and reduces emissions. This research highlights the crucial role of optimizing injection parameters to maximize engine performance and reduce emissions when using alternative fuels.

Keywords: FOME; DEE; butanol; injection pressure; injection timing.

ABBREVIATIONS AND NOMENCLATURES

CI : Compressed Ignition
SAME : Safflower Methyl Ester
BTE : Brake Thermal Efficiency
SFC : Specific Fuel Consumption
HPLC : High-performance Liquid Chromatography
A/F ratio : Air Fuel Ratio
LHR : Low Heat Rejected
bTDC : Before Top Dead Centre

1. INTRODUCTION

Due to the depletion of petroleum reserves, the rising number of automobiles, and increasing environmental pollution, finding alternative fuels is crucial. Biodiesel can be produced from a range of sources, including non-edible oils, edible oils, and animal fats. Fish oil methyl ester, derived Fish oil, stands out as a viable alternative among various options. Despite advancements, challenges remain, particularly with high-viscosity biodiesels like SAME. For example, research has indicated that biodiesel's high viscosity leads to poor atomization and incomplete combustion, which necessitates further optimization (Ahmed et al., 2016; Akash Deep et al., 2017; Balaji Mohan et al., 2014; Cinar et al., 2005; Celikten, 2003; Balaji et al., 2021; Giménez et al., 2004).

Automobile engines today must meet stringent environmental standards, which necessitates maximizing performance while minimizing emissions. CI engines, favoured for their fuel efficiency, reliability, and durability, outperform Spark Ignition engines by consuming less fuel. Key factors influencing CI engine performance include fuel injection pressure, timing, duration, quantity, position, angle, and nozzle size. The fuel injection system is crucial for achieving optimal atomization and combustion. Low fuel injection pressure can lead to wider fuel particle diameters, increased ignition delay, reduced performance, and higher CO, HC, and smoke emissions. Conversely, higher injection pressures enhance atomization, improve air-fuel mixing, and reduce emissions while boosting engine performance (Gui-hua et al., 2004; Zainuddin et al., 2022; Kumar et al., 2016; Kumar & Muniamuthu, 2024; Kumar et al., 2024).

Research supports that increasing fuel injection pressure improves performance and combustion characteristics. For instance, studies have shown that high injection pressures can reduce NO_X and soot emissions without compromising fuel economy. Optimization techniques like Central Composite Design (CCD) suggest that adjustments in injection parameters enhance brake thermal efficiency and reduce fuel consumption. High pressures, such as 600 bar, have been found to improve efficiency with certain fuel mixtures. Additionally, post-injection methods can decrease soot emissions significantly, while various fuel blends, including diesel-tung oil-ethanol mixtures, have shown performance improvements due to reduced combustion periods and higher pressure and heat release rates. Studies on injection timing have revealed mixed results, such as improved efficiency and reduced emissions with specific timings, but also the need for further investigation into optimal conditions. Overall, continuing research and optimization are essential for enhancing the performance and emission characteristics of engines using alternative fuels (Kumar et al., 2024; Wei et al., 2016; Saxena & Maurya, 2017; Nagaraja & Prabhukumar, 2003; Qi et al., 2011; Qi et al., 2017).

The objective of this study is to optimize fuel injection pressure and timing for a Low Heat Rejection (LHR) Compression Ignition (CI) engine running on a blend of 50% Fish Oil Methyl Ester (FOME), 15% Diethyl Ether (DEE), and 35% Butanol. The aim is to enhance engine performance metrics such BTE and SFC while minimizing harmful emissions including NOx, CO, HC, smoke opacity, and aldehydes. By fine-tuning these injection parameters, the study seeks to achieve an optimal balance between efficiency and emissions, demonstrating the viability of this alternative fuel blend for sustainable diesel engine operation.

2. METHODOLOGY

2.1 Experimental Configuration and Procedure

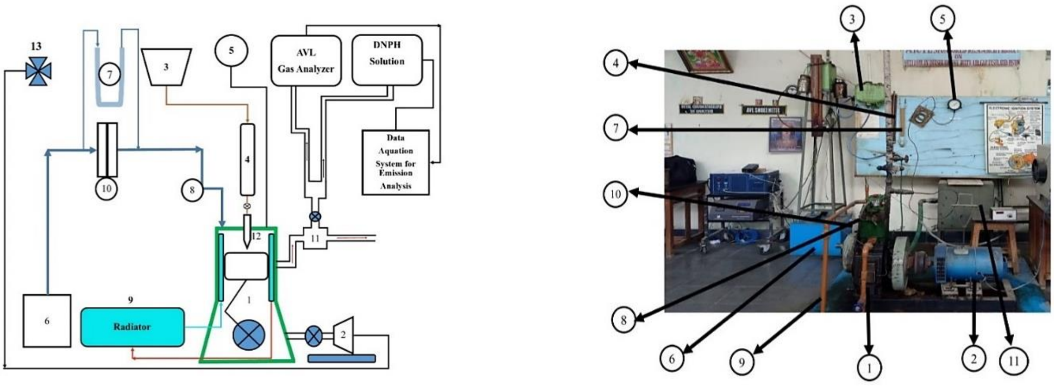
The experimental setup utilized for investigating LHR diesel engines with various fuel blends is depicted in Fig. 1a, while the configurations of the engines are detailed in Table 1.

The experimental setup utilized a compression-ignition engine featuring an aluminum alloy piston, with cylinder dimensions of 80 mm diameter and 110 mm stroke length. It operated at a rated output of 3.68 kW and a rotational speed of 1500 rpm. Fuel consumption was measured via the burette method, while air consumption was monitored using an AVL 5-Gas analyzer setup. Fig. 1a illustrates both the schematic diagram and a photograph of the experimental configuration.

The naturally aspirated engine included a water-cooling system, maintaining an inlet water temperature of 30°C through regulated flow rates. Experiments were conducted at 1500 RPM, with fuel injection pressure of 190 bar, a 27° cranking angle, and a compression ratio of 16.5:1. Engine startup was manual, initially fueled with diesel until achieving steady-state operation. Water flow to the cooling jacket was maintained around 9 LPM. Once stability was achieved, various test fuels were introduced from a separate tank.

Load conditions were regulated using an eddy current dynamometer, incrementally increasing from 0 to 100% in 20% increments for each experimental cycle. Different fuel blends, including FOME, FOME85+DEE15, FOME50DEE15+BTN35, and FOME25+DEE15+BTN60, were evaluated. Key parameters such as manometer readings, engine load, and fuel consumption were systematically recorded throughout the experimental procedures. To study the effects of injection pressure to performance and emission, we investigated those in various injection pressures of 190, 230 and 270 bar. The engine timing used in this work $27^{o}, 29^{o}$ and 31^{o} bTDC. Fig. 1 shows a schematic diagram of the experimental apparatus.

The LHR CI Engine featured a piston composed of two parts: an aluminum piston body and a top crown constructed from a low thermal conductivity material, specifically Ni90, with a thickness of 5mm. When the Ni90 insert was affixed to the engine crown, it featured a 3-mm air gap a configuration identified as optimal for enhancing engine performance. This air gap, as determined from the study, was found to be the most effective thickness for improved engine performance. At a temperature of 500°C, the thermal conductivities of air and Ni90 are recorded as 0.057 W/mk and 20.92 W/mk, respectively. A depiction of the Ni90 insert with the air-gap piston can be observed in Fig. 1b.



a. Schematic layout **b. Photo graphic view**

1. Engine, 2. Electrical Dynamo meter, 3. Fuel tank, 4. Burette, 5. Piezo-electric pressure transducer 6. Air box, 7. U-tube water manometer, 8. Air inlet, 9. Outlet-jacket water flow, 10. Orifice meter 11. Exhaust gas sampling collection,12. Fuel Injector, 13. Dynamometer control

Fig. 1a. Experimental setup

Table 1. Testing Engine Technical details

Engine parameters		Specifications
Engine Type		4 stroke single cylinder, constant speed, direct injection CI Engine
Manufacturer		Kirloskar
Rated power		3.68 kW at 1500RPM
Bore		80mm
Stroke		110mm
Specific volume		0.552 liter
Compression ratio		16.5:1
Cooling type		Water cooling
Insulated insert	Material	Ni90
	Thickness	5mm

2D View of Ni90 fastened LHR Engine   Ni90 Insert   Ni90 fastened LHR Engine

Fig. 1b. LHR engine piston

In experiments using a FOME, DEE, and butanol mixture, aldehydes, including carcinogenic acetaldehyde and formaldehyde, were measured due to their health risks. The DNPH (2,4-dinitrophenyl hydrazine) method was utilized to quantify these aldehydes, where engine exhaust was passed through a DNPH solution to form hydrazones. These were then extracted into chloroform and analyzed using HPLC to determine their concentrations accurately.

3. RESULTS AND DISCUSSIONS

Optimizing fuel injection pressure and timing is crucial for enhancing CI engine performance and reducing emissions. This study examines a CI engine using a blend of 50% Fish Oil Methyl Ester (FOME), 15% Diethyl Ether (DEE), and 35% Butanol, each contributing unique benefits. By varying these parameters, we analyze the impact on metrics like BTE, SFC and emissions including NO_X , CO, HC, smoke opacity, and aldehydes.

3.1 Optimizing the Fuel Injection Pressure

Increasing injection pressure enhances fuel atomization, leading to more efficient combustion. Testing different pressures helps find the optimal level for better spray patterns and combustion efficiency. This optimization is crucial for improving the performance and emissions of engines running on biofuel blends.

The performance analysis of a Low Heat Rejection (LHR) engine using a blend of 50% FOME, 15% DEE, and 35% butanol reveals significant findings by varying injection pressure. At 190 bar, brake power is low described in Fig. 2 due to poor atomization and incomplete combustion. The optimal pressure is 230 bar, where brake power is 4.62% higher than the baseline, providing the best performance across all loads. However, at 270 bar, over-penetration causes mechanical losses, reducing brake power by 2.5%.

SFC also varies with injection pressure. At 190 bar, high fuel consumption results higher due to poor atomization, whereas at 230 bar, the lowest fuel consumption indicates the highest efficiency. From Fig. 3 at 270 bar, increased fuel consumption by 5% compared to 230 bar suggests diminishing returns beyond the optimal pressure.

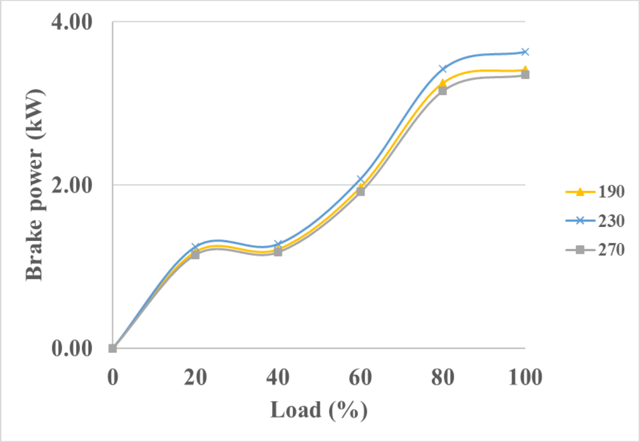


Fig. 2. Variation of brake power with respect to load

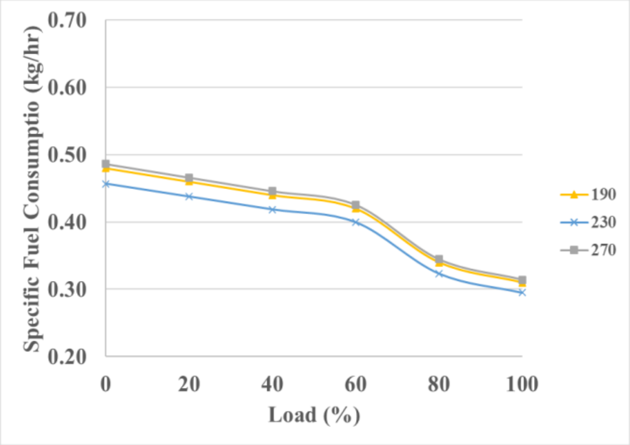


Fig. 3. Variation of SFC with respect to load

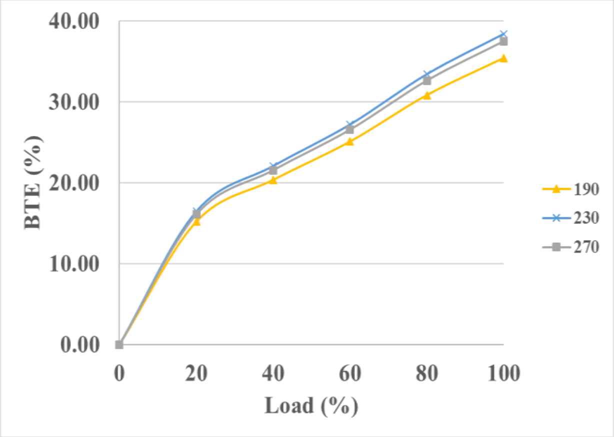


Fig. 4. Variation of BTE with respect to load

Similarly, Brake Thermal Efficiency (BTE) is low at 190 bar due to incomplete combustion, peaks at 230 bar with an 8.52% increase, and slightly decreases at 270 bar by 2.4% due to increased mechanical losses shown in Fig. 4.

Mechanical Efficiency follows a similar trend show in Fig. 5. At 190 bar, reduced mechanical efficiency is attributed to higher friction losses, while at 230 bar, optimal mechanical efficiency shows a 6.9% increase. At 270 bar, efficiency is reduced by 9.9% due to mechanical losses (Qi et al., 2017; Ratnareddy et al., 2013; Riyadi et al., 2023; Abu Baker et al., 2008; Gnanasekaran et al., 2016; Selemani & Kombe, 2022; Shundoh et al., 1992).

The Air-Fuel Ratio (AFR) at 190 bar leads to richer mixtures and incomplete combustion, whereas 230 bar provides an optimal AFR for efficient combustion. At 270 bar, over-penetration causes a slight reduction in AFR.

Volumetric Efficiency is impacted by injection pressure as well. At 190 bar, incomplete cylinder filling reduces efficiency, but at 230 bar, there is a 6.8% improvement shown in Fig. 7. However, at 270 bar, efficiency decreases by 2.9% due to higher temperatures and over-penetration. Emission analysis shows high.

Fig. 8 shows CO emissions at different injection pressures: at 190 bar, emissions are high due to incomplete combustion. At 230 bar, emissions decrease by 17% due to improved combustion efficiency. However, at 270 bar, CO emissions increase by 35% because of rich mixtures and over-penetration of fuel.

Oxides of nitrogen emissions are lower at an injection pressure of 190 bar shown in Fig. 9 due to suboptimal atomization, which leads to incomplete combustion and lower combustion temperatures. However, when the injection pressure is increased to 230 bar, the fuel atomizes more effectively, leading to more efficient combustion and higher temperatures, causing NOx emissions to rise by 33.15% (Reddy et al., n.d.; Kumar et al., 2022; Kumar et al., 2022). At an even higher pressure of 270 bar, the NOx emissions continue to climb by another 21.94%, as the combustion temperatures further increase.

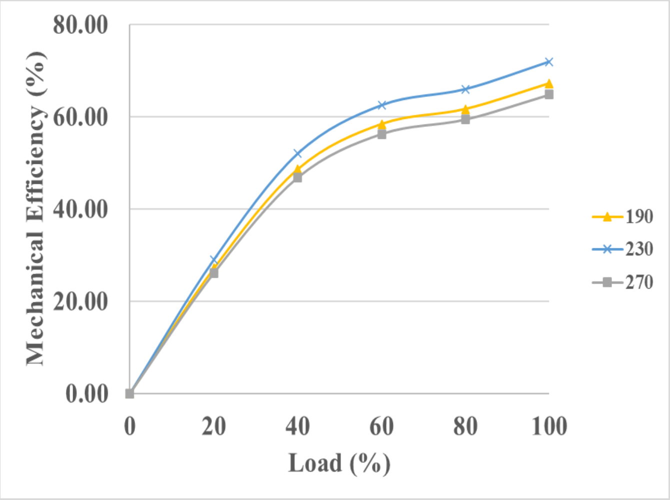


Fig. 5. Variation of Mechanical Efficiency with respect to load

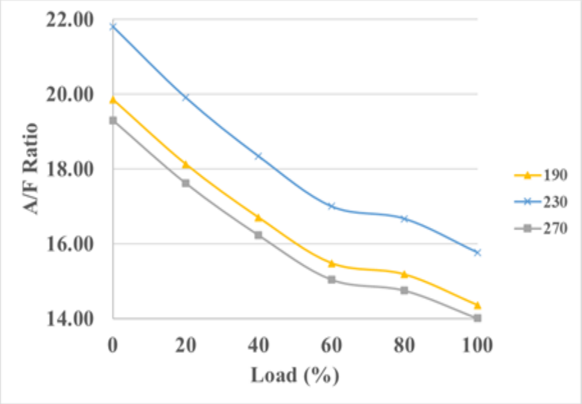


Fig. 6. Variation of A/F ratios with respect to load

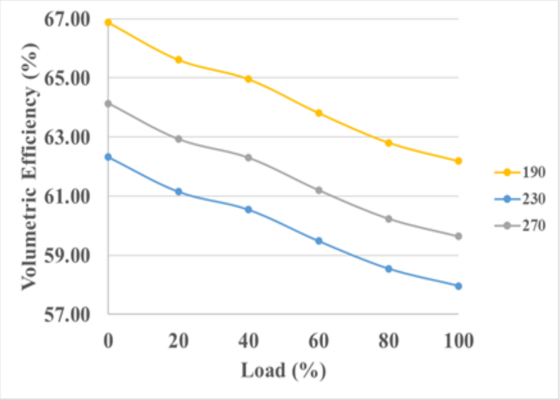


Fig. 7. Variation of Volumetric Efficiency with respect to load

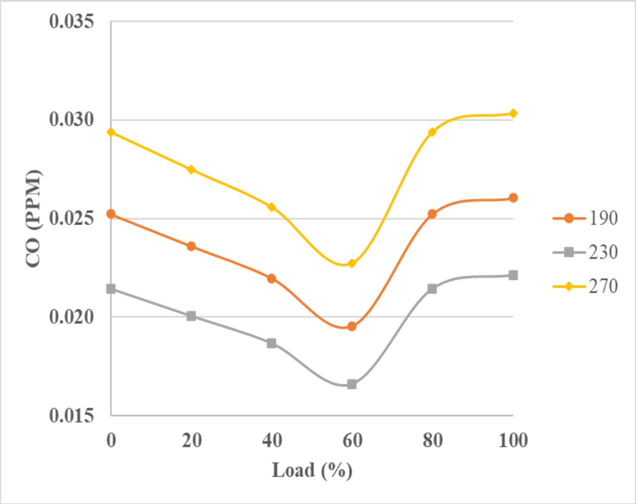


Fig. 8. Variation of CO emission for LHR engine with optimized blend by varying the fuel injection pressure

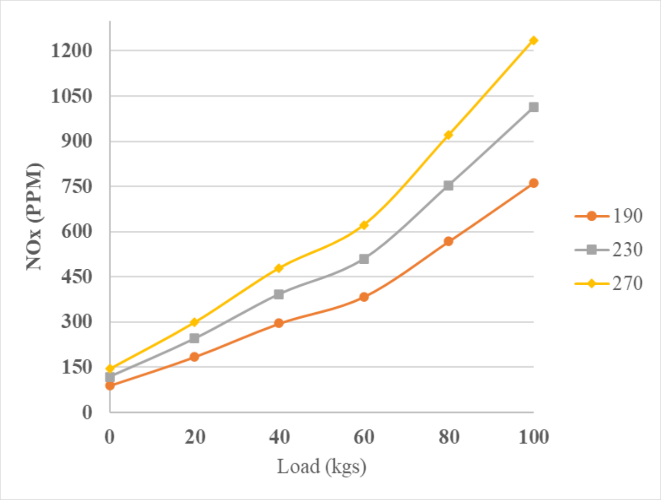


Fig. 9. Variation of NO_X emission for LHR engine with optimized blend by varying the fuel injection pressure

From Fig. 10 Smoke Opacity, an indicator of soot in the exhaust, is initially high at 190 bar due to incomplete combustion and poor atomization. When the injection pressure is optimized to 230 bar, smoke opacity decreases by 15.03% because of better atomization and more complete combustion. However, at 270 bar, the over-penetration of the fuel causes incomplete combustion again, increasing smoke opacity by 19.06%.

Fig. 11 describes variation of Hydrocarbon (HC) emissions are significantly elevated at 190 bar because of incomplete combustion resulting from poor atomization. When the injection pressure is increased to 230 bar, HC emissions are reduced by 47% due to more efficient combustion. At 270 bar, HC emissions are further reduced by 44.6% compared to the baseline, as the fuel continues to burn more completely.

Formaldehyde emissions are high at 190 bar due to incomplete combustion and lower combustion temperatures shown in Fig. 12. At 230 bar, these emissions are reduced by 47.06% because the higher injection pressure improves combustion efficiency. However, at 270 bar, formaldehyde emissions see a slight increase of 5.2% compared to 230 bar, likely due to over-penetration and subsequent combustion inefficiencies.

Acetaldehyde emissions follow a similar trend described in Fig. 13. They are high at 190 bar due to poor combustion. At 230 bar, acetaldehyde emissions drop by 47% as the combustion process becomes more efficient. At 270 bar, there is a slight increase of 0.15% in acetaldehyde emissions compared to the levels at 230 bar, again due to less efficient combustion at this higher pressure.

The optimization of injection timing is crucial for maximizing the performance and reducing emissions of a LHR engine running on a blend of 50% FOME, 15% Diethyl Ether (DEE), and 35% butanol, with an injection pressure of 230 bar. This analysis evaluates how varying the injection timing affects the engine's performance and emissions, focusing on brake power, SFC, BTE, mechanical efficiency, and emissions such as CO, NO_X, smoke opacity, hydrocarbons (HC), formaldehyde, and acetaldehyde.

At lower loads (0-40%), brake power remains relatively low due to suboptimal fuel atomization and incomplete combustion. As the engine load increases, brake power also increases, but it remains less effective compared to higher injection timings. At 27° bTDC, inadequate atomization leads to larger fuel droplets and less efficient combustion, impacting brake power at lower loads.

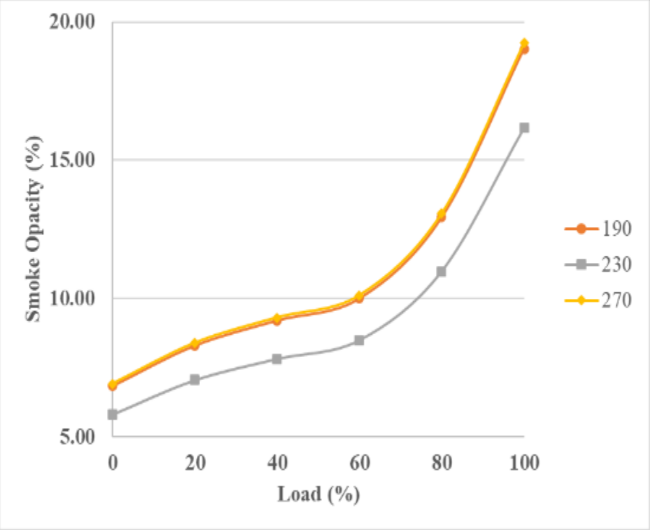


Fig. 10. Variation of Smoke opacity emission for LHR engine with optimized blend by varying the fuel injection pressure

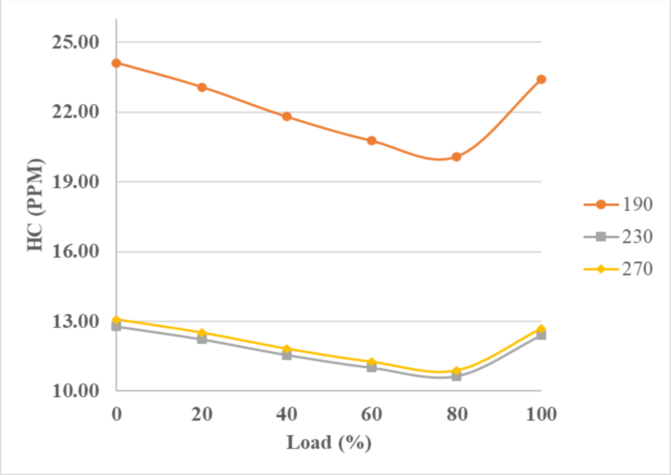


Fig. 11. Variation of Hydro carbon emission for LHR engine with optimized blend by varying the fuel injection pressure

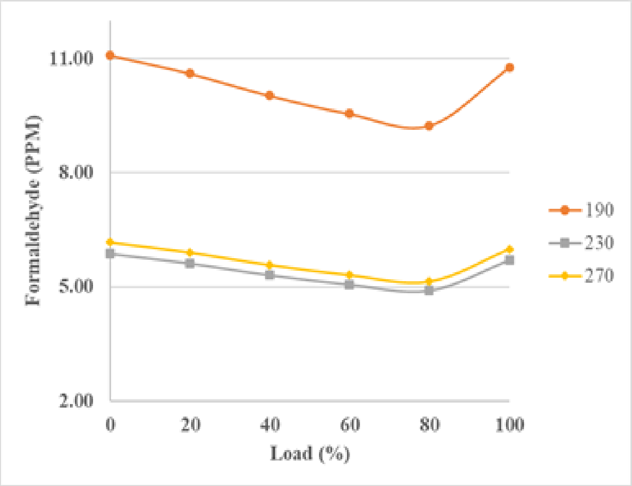


Fig. 12. Variation of Formaldehyde emission for LHR engine with optimized blend by varying the fuel injection pressure

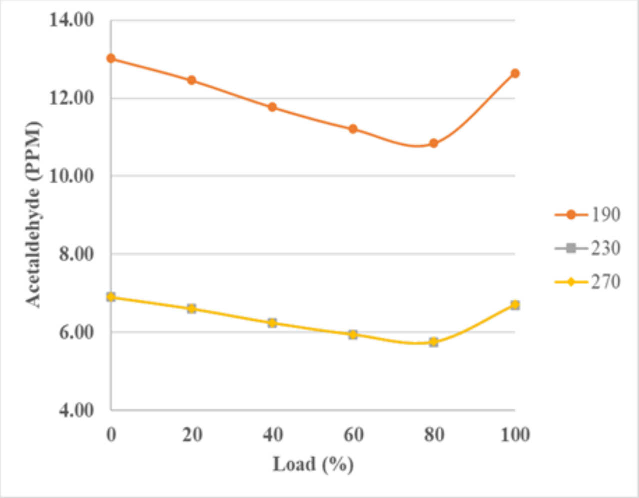


Fig. 13. Variation of Acetaldehyde emission for LHR engine with optimized blend by varying the fuel injection pressure

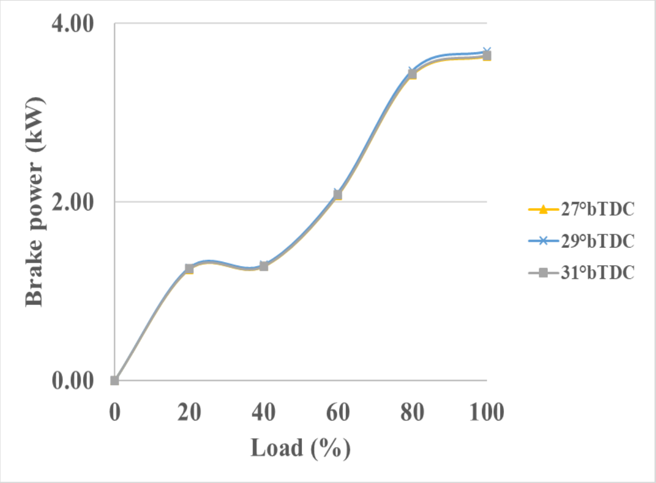


Fig. 14. Variation of Brake power with respect to load

Changing the injection timing to 29° bTDC improves fuel atomization and combustion efficiency, increasing brake power by 1.14% compared to the baseline timing. However, advancing the timing to 31° bTDC results in mechanical losses and fuel over-penetration, reducing brake power by 1.12% at average loads.

At 27° bTDC, poor atomization leads to incomplete combustion and higher fuel consumption, increasing SFC. Adjusting the timing to 29° bTDC improves atomization and combustion efficiency, reducing SFC by 4.9%. However, advancing the timing further to 31° bTDC increases SFC by 6.5% relative to 29° bTDC due to over-penetration and mechanical losses. Therefore, 29° bTDC is optimal for minimizing fuel consumption and maximizing fuel efficiency (Aalam et al., 2015; Aalam & Saravanan, 2015).

At 27° bTDC, poor atomization and incomplete combustion result in lower BTE, especially at lower loads. Adjusting the timing to 29° bTDC significantly improves atomization and combustion efficiency, increasing BTE by 6.97%. Further advancing the timing to 31° bTDC decreases BTE by 4.02% due to increased mechanical losses and potential fuel over-penetration. Thus, 29° bTDC is optimal for achieving the highest BTE.

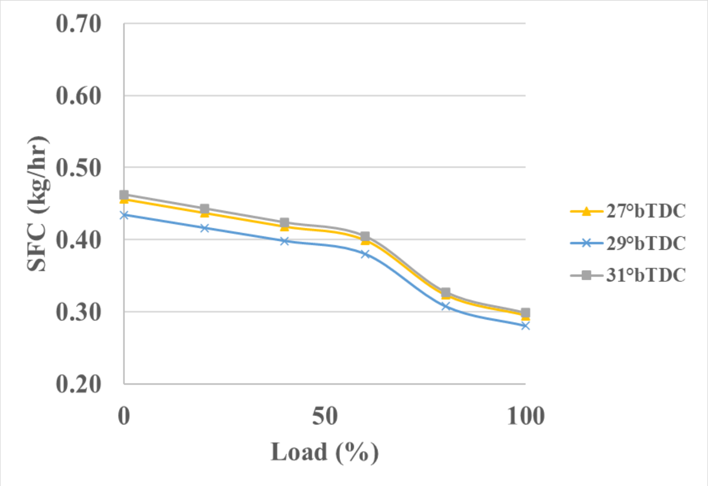


Fig. 15. Variation of SFC with respect to load

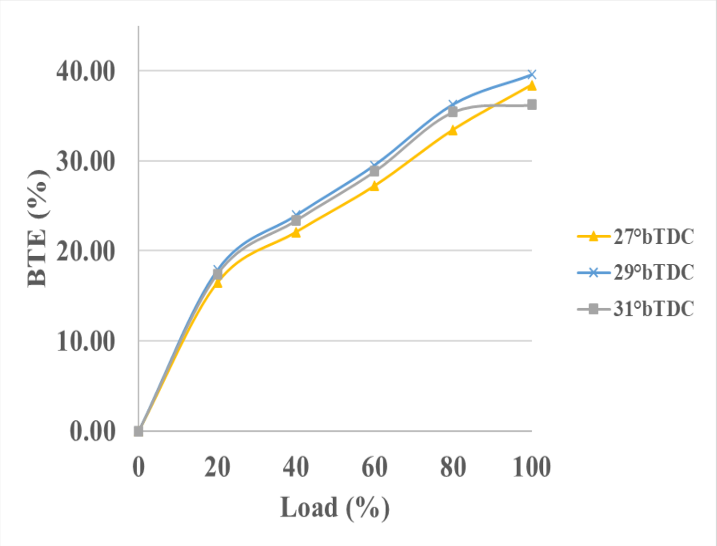


Fig. 16. Variation of BTE with respect to load

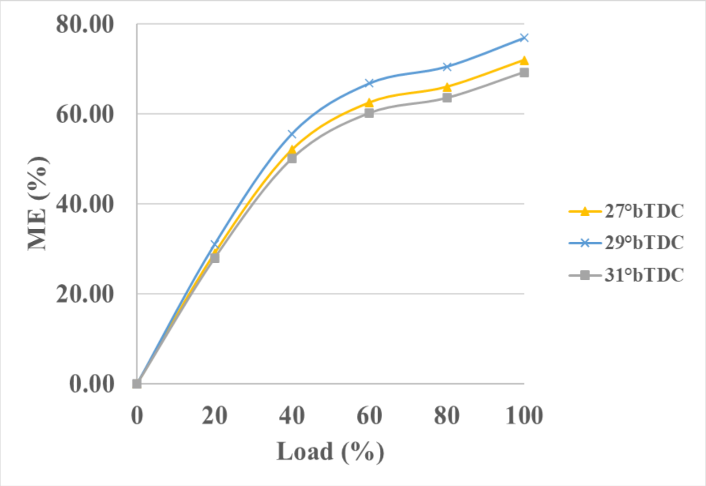


Fig. 17. Variation of Mechanical Efficiency with respect to load

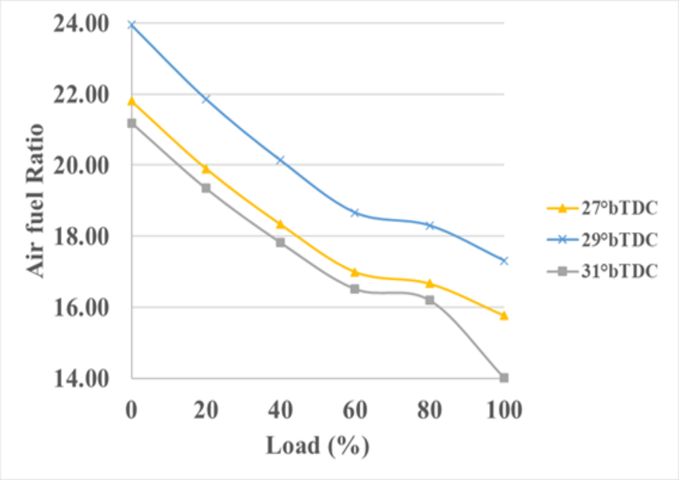


Fig. 18. Variation of A/F ratios with respect to load

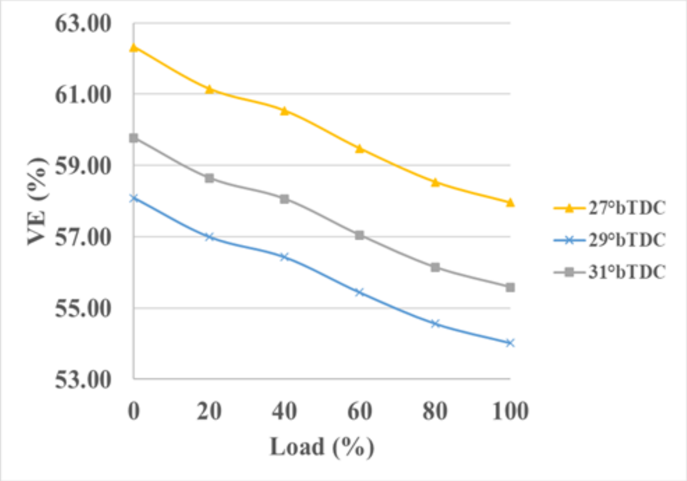


Fig. 19. Variation of Volumetric Efficiency with respect to load

At 27° bTDC, suboptimal atomization leads to increased friction losses and reduced mechanical efficiency. Adjusting the timing to 29° bTDC improves mechanical efficiency by 7%, enhancing fuel atomization and combustion efficiency. However, further advancing the timing to 31° bTDC reduces mechanical efficiency by 10.01% due to additional mechanical losses and fuel over-penetration. Therefore, 29° bTDC is optimal for maximizing mechanical efficiency.

The air-fuel ratio (AFR) is vital for engine performance and emissions control. This study examines AFR variations with load and injection timing in an LHR engine using a blend of 50% FOME, 15% DEE, and 35% butanol. At 27° bTDC, poor atomization results in a richer mixture and higher emissions. Adjusting timing to 29° bTDC improves atomization, achieving an optimal AFR with efficient combustion and enhanced performance. Further increasing timing to 31° bTDC raises AFR, leading to less efficient combustion. Thus, 29° bTDC is optimal for balancing air-fuel mixing and engine efficiency.

Volumetric efficiency, indicating an engine's ability to fill its cylinders with an air-fuel mixture, varies with load and injection timing in an LHR engine using a blend of 50% FOME, 15% DEE, and 35% butanol. At 27° bTDC, suboptimal atomization reduces efficiency. Optimal efficiency is achieved at 29° bTDC, improving intake and atomization. Further increasing timing to 31° bTDC decreases efficiency due to higher temperatures and fuel over-penetration. Thus, 29° bTDC offers the best balance for maximum volumetric efficiency.

At an injection timing of 27° before Top Dead Center (bTDC), carbon monoxide (CO) emissions are relatively high because the fuel atomization is inadequate, leading to incomplete combustion. This poor atomization results in larger fuel droplets that do not burn completely, generating higher levels of CO.

When the injection timing is advanced to 29° bTDC, the CO emissions are significantly reduced by 15%. This reduction is attributed to the improved atomization and combustion efficiency. At this timing, the fuel is better mixed with the air, allowing for more complete combustion and thus lowering CO emissions. However, advancing the timing further to 31° bTDC results in a 37% increase in CO emissions. This increase is due to over-penetration of the fuel into the combustion chamber, which creates localized areas with rich fuel mixtures. These areas do not burn completely, leading to higher CO emissions.

Nitrogen oxides (NOx) emissions increase with more advanced timing because the combustion temperatures are higher. At 29° bTDC, NOx emissions rise by 33% due to the higher peak temperatures achieved during combustion. When the timing is advanced to 31° bTDC, NOx emissions increase further by 22%, as the combustion temperatures continue to rise.

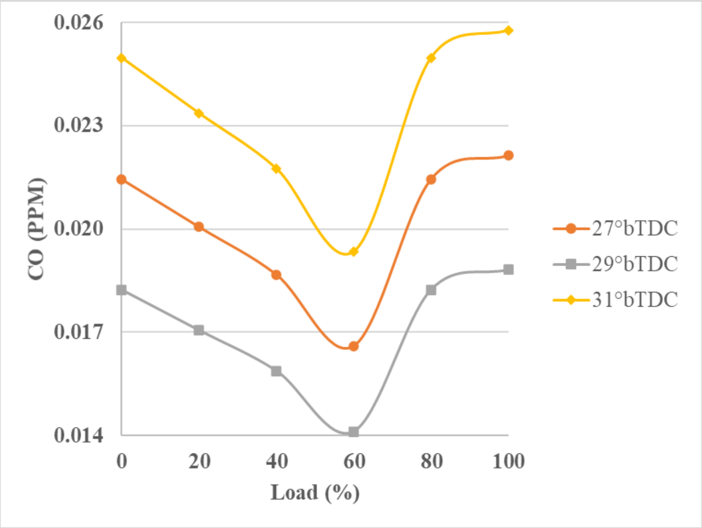


Fig. 20. Variation of CO emission for LHR engine with optimized blend by varying the fuel injection timing

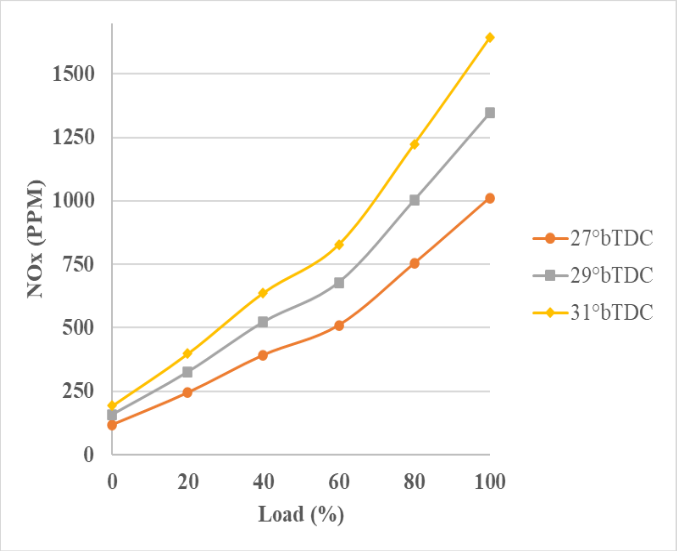


Fig. 21. Variation of NO_X emission for LHR engine with optimized blend by varying the fuel injection timing

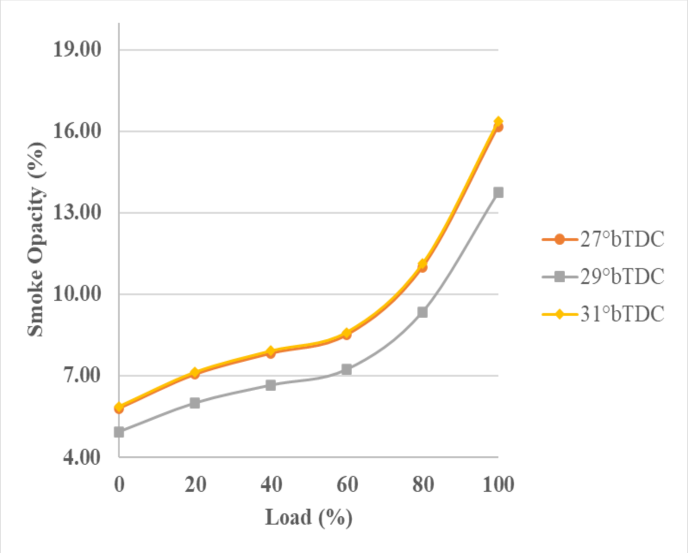


Fig. 22. Variation of Smoke opacity emission for LHR engine with optimized blend by varying the fuel injection timing

Smoke opacity, which indicates the level of particulate emissions, decreases at 29° bTDC because the improved combustion leads to fewer soot particles. However, at 31° bTDC, smoke opacity increases again, likely due to the formation of rich fuel zones that produce more soot.

Hydrocarbon (HC) emissions, which are also indicative of incomplete combustion, decrease at 29° bTDC due to the more complete burning of the fuel. However, there is a slight rise in HC emissions at 31° bTDC, possibly because of the same localized rich mixtures that increase CO emissions.

Formaldehyde and acetaldehyde emissions follow similar trends to CO and HC emissions. The timing of 29° bTDC is optimal for minimizing these emissions, as it represents a balance between improved atomization and avoiding over-penetration. At this timing, combustion is more complete, reducing the formation of these harmful compounds (Aalam et al., 2016; Yesilyurt & Arslan, 2019).

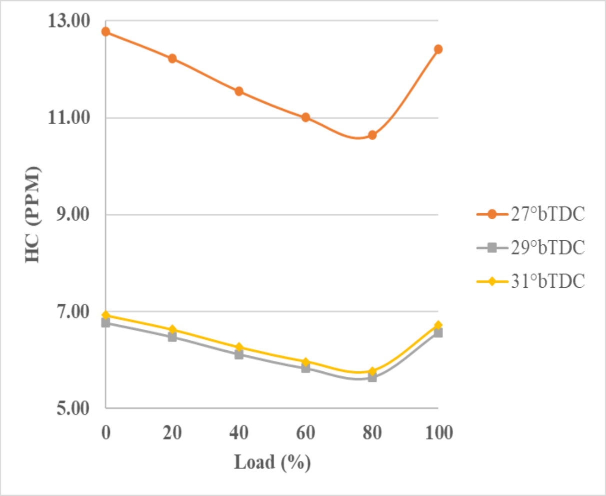


Fig. 23. Variation of Hydro carbon emission for LHR engine with optimized blend by varying the fuel injection timing

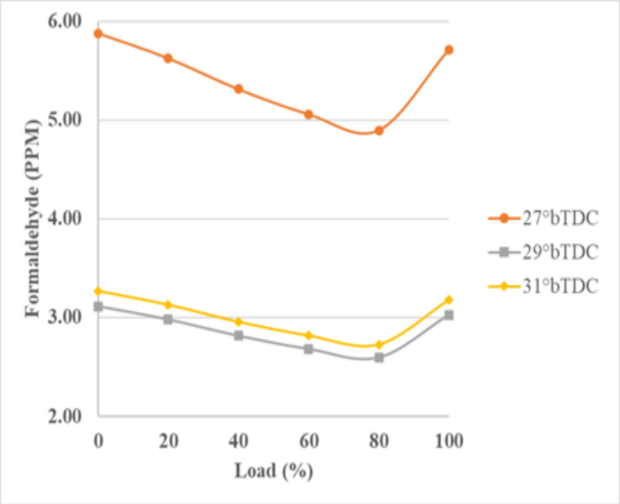


Fig. 24 Variation of Formaldehyde emission for LHR engine with optimized blend by varying the fuel injection timing

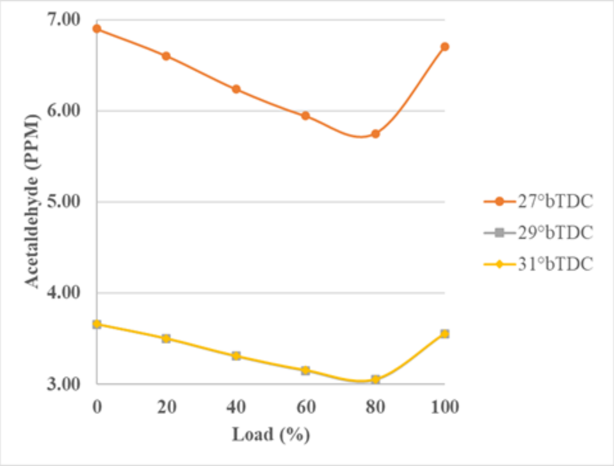


Fig. 25. Variation of Acetaldehyde emission for LHR engine with optimized blend by varying the fuel injection timing

4. CONCLUSIONS

Optimizing fuel injection pressure and timing is essential for maximizing the performance and minimizing emissions of CI engines, particularly when using alternative fuel blends. This study highlights the significant benefits of using a blend of 50% Fish Oil Methyl Ester (FOME), 15% Diethyl Ether (DEE), and 35% Butanol. Each component contributes to improved combustion characteristics, and by fine-tuning the injection parameters, it is possible to enhance Brake Thermal Efficiency (BTE), reduce Specific Fuel Consumption (SFC), and lower emissions of NOx, CO, HC, smoke opacity, and aldehydes. The findings underscore the importance of precise injection parameter optimization in leveraging the advantages of alternative fuels for CI engines.

- Increasing injection pressure enhances fuel atomization and combustion efficiency in biofuel engines. For a LHR engine with a 50% FOME, 15% DEE, and 35% butanol blend, the optimal pressure is 230 bar, improving brake power by 4.62%, while 270 bar causes a 2.5% decrease due to over-penetration.
- Specific Fuel Consumption (SFC) is highest at 190 bar and lowest at 230 bar, indicating optimal efficiency, while Brake Thermal Efficiency (BTE) peaks at 230 bar with an 8.52% increase but slightly drops at 270 bar. Mechanical Efficiency also peaks at 230 bar with a 6.9% improvement, decreasing by 9.9% at 270 bar.
- Volumetric Efficiency improves by 6.8% at 230 bar but decreases by 2.9% at 270 bar. CO emissions are highest at 190 bar, reduced by 17% at 230 bar, and rise by 35% at 270 bar. NOx emissions increase by 33.15% at 230 bar and by 21.94% at 270 bar.
- Smoke opacity decreases by 15.03% at 230 bar and increases by 19.06% at 270 bar. HC emissions drop by 47% at 230 bar and slightly more at 270 bar, while Formaldehyde emissions are reduced by 47.06% at 230 bar but increase by 5.2% at 270 bar.
- Optimizing injection timing is key for performance and emission control in LHR engines. At 29° bTDC, brake power improves by 1.14%, SFC decreases by 4.9%, and BTE increases by 6.97%, while at 31° bTDC, performance metrics generally decline.
- CO emissions decrease by 15% at 29° bTDC but increase by 37% at 31° bTDC, NOx emissions rise by 33% at 29° bTDC and by 22% at 31° bTDC. Smoke opacity and HC emissions show similar trends, decreasing at 29° bTDC but increasing at 31° bTDC. Formaldehyde and acetaldehyde emissions are minimized at 29° bTDC.

The experiments conducted revealed that optimizing the injection pressure up to 230 bar and fine-tuning the injection timing to 29° bTDC resulted in the best overall engine performance and emission characteristics. The findings underscore the importance of precise control over fuel injection parameters to achieve the desired balance between efficiency, performance, and environmental impact when using alternative fuel blends in CI engines.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of this manuscript. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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