Comparative Study of HCCI, PCCI, and RCCI Engine Technologies Using Alcohol Fuels

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1.Abstract:

This comparative study explores the advancements and characteristics of three innovative engine combustion technologies: Homogeneous Charge Compression Ignition (HCCI), Partially Premixed Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI). The focus of this study is on the use of alcohol fuels in these combustion modes, examining their potential benefits in terms of efficiency, emissions, and overall performance. By comparing these technologies, we aim to provide insights into the strengths and limitations of each approach, shedding light on the feasibility of utilizing alcohol fuels in modern internal combustion engines.

Low temperature combustion (LTC) strategies can reduce NOx and soot emissions while increasing thermal efficiency. Commercial widespread adoption of LTC Strategies must address challenges such as limited operating load range, insufficient ignition timing control, and high emissions of unburned hydrocarbons and carbon monoxide. Conventional engine designs and fuels may not be well-suited for LTC modes, leading to challenges. To improve long-term care strategies, it's crucial to replace traditional diesel fuel with appropriate alternatives. This study compares three LTC strategies (Homogenous Charge Compression Ignition, Premixed Charge Compression Ignition, and Reactivity Controlled Compression Ignition) to conventional diesel combustion in a light-duty diesel engine Develop an alternative fuel strategy to increase operating range and reduce emissions. The fuel selection strategy based on the fundamental fuel property requirements of the three LTC strategies has been discussed in detail. The baseline reference data is established by comparing three LTC strategies to conventional diesel combustion. Diesel and gasoline are used as reference fuels at 40% load, which is the highest common achievable load among all three strategies. The study examines the impact of alternative fuels on three LTC strategies, aiming to address

shortcomings. The study found that using alternative fuels can significantly reduce HC and CO emissions while increasing engine load range in the three LTC strategies.

2.Introduction:

LTC strategies in internal Combustion engines emit low levels of pollutants while producing high amounts. Engine performance based on chemically controlled combustion temperature. Engine strategies are classified into three types: premixed charge compression ignition (PCCI), homogenous charge compression ignition (HCCI), and reactivity control compression ignition (RCCI) engines. LTC aims to produce a lean, homogeneous air-fuel mixture that reduces emissions while maintaining engine power output. LTC uses a variety of fuel supply strategies and types, including low reactivity fuels (e.g., gasoline and alcohols) and high reactivity fuels (e.g., diesel, dimethyl ether).

LTC strategies use a combination of LRF and HRF. Several studies have shown that alcohol fuels are more popular than other LRFs for LTC engine applications. LTC engines use four types of fuels as LRFs: ethanol, methanol, butanol, and n-butanol. These fuels are typically combined with HRFs such as diesel (nheptane in numerical studies) or used as single fuels at high engine loads due to cooling effects. Alcohol fuels have varying chemical and physical properties, which can impact engine combustion and emissions. The study examines the correlation between pollutants, local equivalence ratio, and temperature in conventional diesel combustion (CDC), HCCI, PCCI, and RCCI.

Figure 1 shows that CDC areas have high local equivalence ratios and temperatures, while LTC strategies operate in poor equivalence ratios and lower maximum temperatures, resulting in reduced NOx and soot emissions. LTC zones exhibit minimal oxidation of unburned hydrocarbons and carbon monoxide. LTC strategies can reduce NOx and soot emissions while maintaining diesel cycle efficiencies. However, they often increase uHCs and CO emissions and reduce combustion controllability. These strategies improve the maximum pressure rise rate (PPRR) of combustio.

Methanol, ethanol, and butanol are commonly used alcohol-based fuels in both spark ignition (SI) and compression ignition (CI) cycle engines applications. The chemical structure of alcohol is $C_nH_{2n+1}OH$.
Higher octane alcohols can reduce knocking in SI engines, while fuel oxygen in alcohol diesel blends reduces soot formation in compression ignition engines.
Blending alcohol reduces emissions in both SI and CI ICEs.
The LTC strategy improves fuel atomization and mixing, lowering the local equivalence ratio and combustion temperature . This reduces NOx and PM emissions simultaneously.
Figure 1 shows temperature and equivalence ratio changes across operational regimes for CDC, HCCI, PCCI, and RCCI.
Alcohol fuels offer the benefits of HCCI combustion, including higher octane numbers, a wider range of equivalence ratios, and reduced emissions. Using alcohol fuel in an RCCI engine improves thermal efficiency and reduces exhaust pollutants. LTC strategies are primarily concerned with CO and HC emissions, which are caused by Misfire refers to incomplete combustion of fuel in an engine . The combustion temperature of homogeneous lean mixtures strongly affects CO emissions. In ultra-lean mixtures, the

temperature becomes too low to complete oxidation reactions, resulting in high CO levels during HCCI combustion. Figure 2 shows how CO emissions vary for natural gas, ethanol, and methanol fuels during HCCI combustion.

Conventional spark ignition (SI) and compression ignition (CI) combustion systems have limitations that affect their performance.1 SI engine performance is limited by knock and higher NOx emissions. Similarly, CI engines' performance is limited by increased smoke and NOx emissions.2-4 To comply with strict emission regulations, modern vehicles use costly after-treatment devices that require regular maintenance. Adopting low temperature combustion (LTC) strategies can reduce exhaust emissions without compromising engine performance, making them a potential solution to meet stringent emission standards.LTC strategies bypass NO and soot formation zones by creating a homogeneous lean mixture and lowering the in-cylinder temperature, as illustrated in Figure 1(a). Each strategy employs various methods to achieve the LTC strategies HCCI, PCCI and RCCI with conventional diesel combustion (CDC).

In port fuel-injected HCCI (PFI-HCCI), fuel is introduced into the intake manifold, similar to a conventional gasoline spark-ignited combustion system. The external. The mixture preparation strategy aids in the creation of a homogeneous mixture, thereby reducing the local fuel-rich mixture. Early fuel injection in HCCI leads to poor control over ignition timing and combustion phasing.8-11 In PCCI, fuel is injected earlier than in conventional diesel combustion, but in the engine cylinder. This allows for better ignition timing control and a wider operating load range compared to HCCI. The fuel-air mixture introduction method reveals that PCCI produces more gradients and less homogeneity than HCCI.11-16 Unlike HCCI and PCCI, RCCI employs a dual fuel strategy. This type of engine uses both low-reactivity fuel (introduced in port) and high-reactivity fuel (introduced in combustion chamber), such as gasoline and diesel. RCCI achieves different loads by varying the ratio of port-injected and direct-injected fuel, allowing for a wider operational window compared to other LTC strategies.

LTC strategies significantly reduce NOx and soot emissions while maintaining or improving engine thermal efficiency compared to CDC.
However, LTC strategies result in higher HC and CO emissions due to lower cylinder temperatures that reduce oxidation. LTC strategies face challenges such as increased pressure rise rates, limited load range, and lack of combustion control. Resolving these shortcomings is crucial for the commercial viability of LTC strategies. Using alternative fuels can help mitigate these challenges.
Using alternative fuels in LTC strategies can address transportation-related greenhouse gas emissions and reduce reliance on fossil fuels. Blending alcohol fuels, including ethanol and propanol. Combining butanol with diesel improves fuel properties, increasing ignition delay and oxygen content. Alcohols and alternative fuel blends reduce HC and CO emissions while improving brake thermal efficiency.
The literature review explores HCCI, PCCI, and RCCI strategies in various engine types using conventional and alternative fuels. The study does not compare the three strategies to alternative fuels. This study compares HCCI, PCCI, and RCCI strategies for alternative fuels in a single-cylinder diesel engine used for agricultural water pumping. The production engine is modified to support multiple LTC strategies. Initially, a comparison of three LTC strategies (HCCI, PCCI, and RCCI) with CDC was performed.

Various alternative fuels have been tested in three LTC strategies. The results suggest a suitable alternative fuel and optimal LTC strategy to improve engine performance and reduce exhaust emissions.

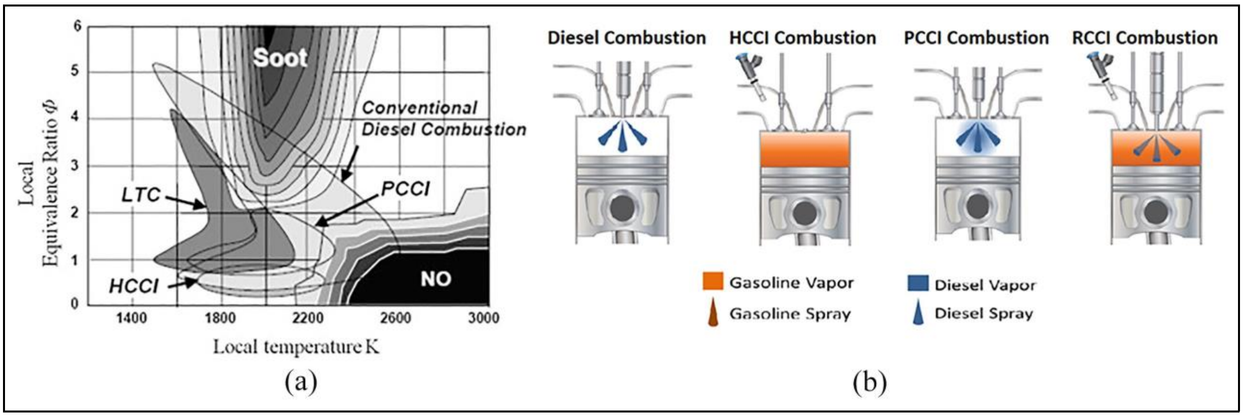


Figure 1. (a) Local equivalence ratio and temperature with NO and soot formations zones in LTC and conventional diesel combustion; (b) Comparison of HCCI, PCCI, and RCCI strategies with conventional combustion.

3.LTC strategies of HCCI, PCCI, and RCCI :

HCCI, PCCI, and RCCI combustion are effective LTC strategies.
Figure 3 illustrates key characteristics of LTC derivatives and their comparison to traditional combustion methods.

3.1 HCCI Combustion:

HCCI is an early diesel combustion concept that combines the benefits of CI (stratified charge compression ignition) and SI (homogeneous charge spark ignition) combustion modes. It uses premixed charge, similar to SI mode, but auto ignition occurs similarly to CI mode. This concept was initially proposed by Onishiet. Who used it in a gasoline-fueled two-stroke engine to improve combustion stability during partial load conditions. His group named the combustion technique "Active Thermo-Atmospheric Combustion" (ATAC). The HCCI combustion mode injects fuel significantly before the start of combustion (SoC) in the intake stroke.
This provides enough time for a homogeneous fuel-air mixture to form. In contrast to SI (flame propagation) and CI (locally rich flame front) combustion modes, this homogeneous mixture burns simultaneously at multiple locations in the combustion chamber. Chemical reaction kinetics are primarily responsible for combustion phasing, which differs from injection timing. HCCI combustion was easily implemented in SI engines . However, diesel-fueled HCCI engine development faces challenges due to lower volatility.

However, these strategies led to poor combustion due to inefficient fuel-air mixing. The main challenge in successfully demonstrating diesel HCCI is its low volatility. Ryan and Callahan used an external fuel-air mixture preparation technique and diesel to improve the quality of the intake air stream. Singh et al. created a 'fuel vaporizer' to investigate the combustion, emissions, and performance of diesel and biodiesel-fueled HCCI combustion. Although HCCI combustion was found to have better emission characteristics than conventional CI combustion, it was limited by lack of combustion control, higher HRR, and higher levels of HC and CO emissions, especially at higher engine loads.

3.2 PCCI Combustion :

PCCI combustion is similar to HCCI and can be easily implemented in modern CRDI diesel engines. PCCI combustion ignites a lean fuel-air mixture through compression, avoiding soot and NOx formations in high-temperature regions. PCCI combustion has similar emission characteristics to HCCI combustion, but provides better control over combustion events.
Controlling in-cylinder charge motion, compression ratio, fuel injection parameters, and EGR can affect key combustion parameters such as ignition delay and duration. studied PCCI combustion and developed an optimized fuel injection strategy.

Multiple injections, combined with EGR, resulted in lower NOx reduction and PM emissions. Multiple fuel injection strategies improved fuel-air mixture homogeneity, while optimal EGR reduced in-cylinder temperature below the NOx formation threshold. Despite its benefits, PCCI combustion has yet to be implemented in commercial engines due to limited control over combustion events at higher engine loads. Excess fuel at high engine load causes high HRR, which can damage engine components.

3.3 RCCI Combustion :

RCCI combustion technique was demonstrated for the first time at Engine Research Center, University of Wisconsin, Madison, USA.
RCCI combustion is a dual-fuel technique that uses port fuel injection (PFI) or early dire ct injection (DI) to create a homogeneous fuel-air mixture from low-reactivity fuels like gasoline, alcohols, and compressed natural gas (CNG). To control the start of SoC, a high-reactivity fuel (e.g. mineral diesel/biodiesel) is injected directly into the combustion chamber with optimized start of injection (SoI) timing. The fuel's high reactivity causes combustion to begin in high zones and progress to low zones in the combustion chamber. Spatial stratification of fuel reactivities can control RCCI combustion parameters, including SoC and combustion duration.

The reactivity gradient influences combustion duration, PRR, and noise levels. The SoC is influenced by the amount of low and high reactivity fuel, with a higher proportion of high reactivity fuel leading to improved performance. The dualfuel strategy allows for better control over combustion phasing. Combustion phasing is primarily determined by the concentration and timing of high-reactivity fuel. Table 1 compares a few LTC modes to conventional combustion.
Previous research has explored various derivatives of LTC combustion, including HCCI, PCCI, and RCCI, for low-load applications in both light-duty and heavy-duty engines.

LTC derivatives have potential for reducing NOx and soot emissions, but lack of combustion control can cause knocking at high loads and misfire or unstable combustion at low loads (especially during engine start). These challenges limit operation to a narrow range and do not address all operating conditions. The limited operational range of LTC is the main barrier to its commercialization. Researchers attempted to expand the operational range of LTC using turbochargers, superchargers, and various injection strategies. However, LTC still struggles to cover the entire range of commercial diesel engines.

After analyzing the observations, it was determined that real-world applications of LTC require a more conventional diesel combustion mode in areas where LTC is not feasible. For high load ranges, LTC cannot reduce NOx and soot simultaneously, so CI mode is used to maximize efficiency and fuel economy. The'mode switching technique' was demonstrated as an intermediate solution to address this issue. The mode switching technique allows engines to operate in both LTC and CI combustion modes based on operating conditions. It is a promising solution for commercializing LTC technology.

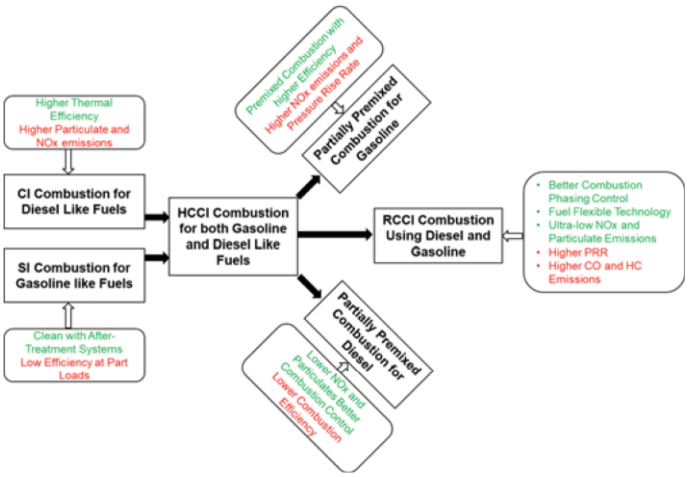


Figure 2: Different combustion strategies.

	SI	CI	HCCI	PCCI	RCCI
Ignition type	Spark ignited	Compression ignited	Compression ignited	Compression ignited	Compression ignited
Fuel type	High octane	High cetane	Blend of liquid or gaseous fuels	Blend of liquid or gaseous fuels	PFI of high octane fuel and DI of high cetane fuel
Power output Control	Air-flow control	Fuel-flow control	Fuel-flow control	Fuel-flow control	Fuel reactivity stratification
Fuel-air mixture Condition	Near stoichiometric air–fuel ratio	Lean air–fuel ratio	Lean air–fuel ratio or charge dilution	Lean air–fuel ratio or high charge dilution	Air–fuel ratio stratification, typically without charge dilution
Combustion control mechanism	Flame propagation Speed	Time of fuel vaporization and mixing	Chemical kinetics	Chemical kinetics and injection timing	Chemical kinetics and fuel reactivity
Particulate and NOx emissions	Cleaner with three-way catalyst	Higher particulate and NOx (without after-treatment)	Lower NOx and particulates	Lower NOx and particulates	Ultra-low NOx and particulates
Other emission characteristics	Higher CO_2	Lower CO_2	Higher HC and CO and lower CO_2	Higher HC and CO and lower CO_2	Very high HC and CO (without after-treatment) and lower CO_2

Table 1: Comparison of SI, CI, HCCI, PCCI and RCCI combustion strategies.

4.Fuel selection method and fuel characteristics:

Fuel selection is based on operational and emission-related challenges for the three LTC strategies. Table 5 summarizes challenges and strategies for alternative fuels, including HCCI, PCCI, and RCCI.
To improve mixture homogeneity and achieve a suitable cetane number for HCCI, an ignition improver additive was added to gasoline.36-38 This addresses the load range and combustion phasing challenges in HCCI. Oxygenated alternative fuels reduce higher HC and CO emissions.36,37,39,40 Butanol's cetane number is comparable to gasoline, allowing for a better understanding of the impact of fuel-bound oxygen content

on LTC. Similarly, butanol, a low reactive and oxygenated fuel, is blended with diesel to reduce unburned emissions and improve operating range.

Two port-injected alternative fuels and three direct-injected alternative fuels were evaluated and compared.
Gasoline is the primary fuel for port injection. Two oxygenated alcohols, ethanol and butanol, have been blended with gasoline to create alternative PFI fuels. For RCCI DI fuel, the base diesel fuel is blended with low reactive fuels such as gasoline and butanol, as well as high reactive oxygenated Karanja biodiesel (41-43). RCCI aims to reduce high HC and CO emissions through the use of alternative fuels during operations.

Table 6 summarizes the physiochemical properties of the tested fuels. The fuels used in this work include commercial gasoline, diesel, and Karanja biodiesel. Butanol and 2-Ethyl hexyl nitrate (EHN) are scientific grade and 99.9% pure.
All test fuel samples' engine fuel properties are analyzed using the ASTM standard test procedure.
EHN has been added to the gasoline to achieve the various cetane ratings. Adding 5% EHN to gasoline increases the cetane number from 19 to 33, while 7.5% EHN increases the cetane number to 47, comparable to diesel fuel.

Table 2. Challenges associated with HCCI, PCCI and RCCI strategies and suitable alternative fuels.

Property	HCCI	PCCI	RCCI
Operational challenge	Limited load range, combustion phasing and ignition control	High EGR requirement, Limited load range	PFI to DI ratio optimization
Emission challenge	High HC and CO	High HC, CO, and smoke	High HC and CO
Fuel reactivity	Moderate	Moderate	PFI: low DI: High
Volatility	High	Optimal	PFI: high DI: Low
Suitable fuels	Butanol, gasoline with additive	Butanol and gasoline blends with diesel	PFI: alcohol fuels,DI: biodiesel

Table 3. Test fuel properties

Fuel\Property	CN	LHV (MJ/kg)	Density (kg/m³)	Viscosity (mm²/s)	Vapor Pressure (kPa)	Latent Heat of vaporization (J/g)
Gasoline/G100	\ 19*	43	784	0.5573	;9.0	305
Diesel/D100	47	45.4	813	2.825	;1	270
Butanol	;25	33.1	810	2.63	11.9	582
Ethanol	;8	26.8	789	1.08	15.9	904

Biodiesel (Karanja)	52.8	35.9	897	2.8253	;1	-
G100_EHN2.5	25.4*	42.5	805.3	1.3641	-	-
G100_EHN 5	33*	40.7	781.6	0.5524	-	-
G100_EHN 7.5	45.4*	41.5	781.2	0.5505	-	-

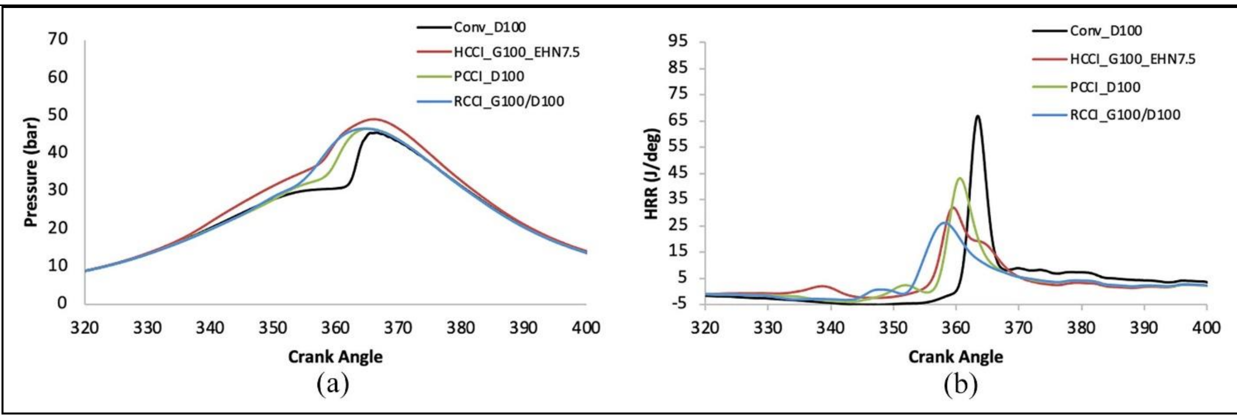


Figure 3. Comparison of pressure (a) and HRR (b) profiles of LTC strategies and CDC operated with reference fuel at 40% rated load condition.

4.1 Comparison of LTC strategies and CDC with base fuels:

To compare engine performance and exhaust emissions between HCCI, PCCI, and RCCI strategies, a reference fuel is used first. Figures 3(a) and (b) show the pressure and heat release rates of three LTC strategies using CDC at 40% rated load. The reference fuel for PCCI operation is diesel injected at 40 bTDC with 60% EGR, resulting in low NOx and smoke emissions. RCCI reference fuels are fixed as gasoline (PFI) and diesel (DI). The PFI to DI fuel ratio in RCCI varies based on the heating value of the PFI and DI fuel. In RCCI operations, the fuel energy ratio (PFI fuel to DI fuel energy) ranged from 21.7% to 64.5%.
at 20% to 80% load (1.06–4.25 bar BMEP).

HCCI was tested with a gasoline-EHN blend. With 7.5% EHN (G100EHN7.5), it has a similar cetane number (CN 45.4) but higher volatility than diesel. The 40% load point was chosen for all three LTC. Strategies could achieve this load condition using reference fuel. CDC has a steep pressure rise profile, while HCCI, PCCI, and RCCI combustion profiles are smoother and show wider HRR profiles.
The location and occurrence of low-temperature heat release (LTHR) also differ significantly. The pressure profile reflects the LTHR event, with HCCI showing slightly higher pressure at early crank angles. The CDC lacks the LTHR event that distinguishes LTC strategies.

The HRR profile indicates the presence of LTHR in all LTC strategies. The LTHR event occurs first in the HCCI, then in the RCCI and PCCI. The presence of LTHR indicates charge homogeneity in the combustion chamber. HCCI is completely premixed, while RCCI is partially premixed and PCCI is least premixed due to in-cylinder fuel injection. To analyze temperature variations, we calculate the pressure-averaged mean in-cylinder temperature for all three low-temperature combustion strategies, including CDC. Direct measurement of in-cylinder temperature is beyond the scope of this work. The ideal gas law, pV= mRT, is used to calculate the pressure averaged in cylinder mean temperature. p and V represent the instantaneous cylinder pressure and volume, respectively.

The gas mass (m) is calculated based on the volume captured during the intake process after the valve closure event. R is the specific gas constant for air, which is 285.05 J/kgK. The maximum mean in cylinder temperature for CDC is 1709 K. Similarly, the maximum values of mean in-cylinder temperature for PFI-HCCI, PCCI, and RCCI are 1636, 1604 and 1628 K, respectively.

The spread of the HTHR differs significantly between LTC strategies and the CDC. HCCI and RCCI have longer combustion durations, followed by PCCI and CDC. Figure 4 shows a log scale plot for engine exhaust emissions and BTE. LTC strategies result in significantly lower NOx and smoke emissions and higher BTE compared to CDC. On the downside, all LTC strategies emit more HC and CO than the CDC. The LTC strategy with the lowest HC and CO emissions is HCCI, followed by PCCI and RCCI. In terms of brake thermal efficiency, PCCI is the most efficient, followed by RCCI and HCCI.

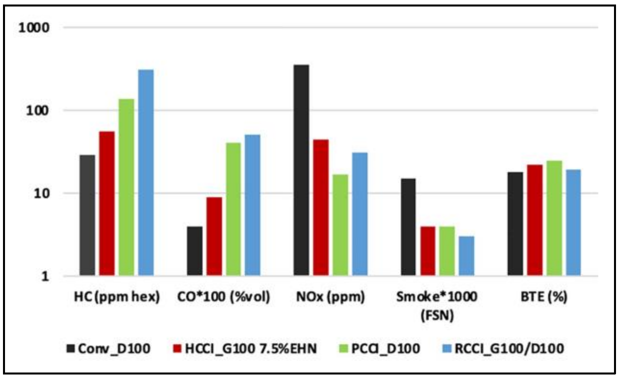


Figure 4. Comparison of exhaust emissions and BTE (in log scale) of LTC strategies and CDC operated with reference fuel at 40% rated load condition.

4.2 LTC strategies operated with alternative fuels:

LTC strategies are fuel-flexible and adapt to changes in fuel composition and properties. The experiments use alternative fuels to address challenges in HCCI, PCCI, and RCCI strategies.

4.2.1 PFI-HCCI operation with alternative fuels:

Experiments with five fuel blends in port fuel-injected HCCI (PFI-HCCI) are conducted to assess the impact of cetane number (using gasoline with ignition improver), fuelbound oxygen content (using butanol), and volatility (using diesel and Karanja biodiesel) on the challenges of HCCI strategy, including narrow load range and high HC and CO emissions. Figure 5 shows the pressure and HRR profiles for PFI-HCCI with alternative fuels. Figure 6 shows the log scale for engine exhaust emissions and performance. Smoke and NOx emissions are significantly lower in HCCI compared to CDC.

In the HCCI mode, all test fuels emit less than 40 ppm of NOx and less than 0.1 FSN of smoke. Table 7 compares the engine's operable load range with tested alternative fuels in HCCI mode.

The use of an ignition improver (EHN) boosts the cetane number. Adding 2.5% and 5% (by volume) EHN to gasoline results in cetane numbers of 25 and 33, respectively. The cetane number differs significantly between these two fuel blends, but their other properties are nearly identical. Figures 5(a) and (b) depict the pressure and heat release rate (HRR) profiles of gasoline containing 2.5% EHN (G100_EHN 2.5) and 5% EHN (G100_EHN 5). G100_EHN5 exhibits higher peak pressure and shorter ignition delay compared to G100_EHN2.5. Adding a cetane improver to the HRR plot accelerates low-temperature heat release (LTHR). In emission trends, increasing the cetane number reduces HC and smoke emissions while increasing brake thermal efficiency.

However, increased in-cylinder temperatures lead to higher NOx emissions. Table 7 shows the load range in HCCI using alternative fuels. The G100EHN_2.5 engine can operate at a load range of 40% (2.12 bar BMEP) to 70% (3.71 bar BMEP), with higher levels.

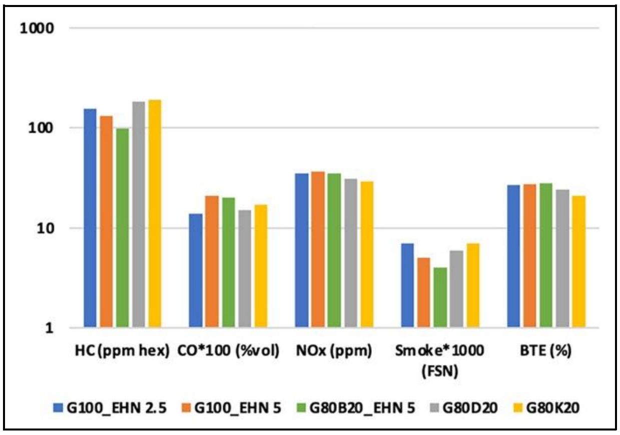
The use of cetane number fuel (G100EHN_5) improved low load range and reduced misfires. However, it limits high load range operation by exceeding the maximum pressure rise rate limit due to the high cetane effect.
The experimental test procedure previously covered the limits for misfire and maximum pressure rise rates.

To study the impact of oxygenated fuel, butanol was chosen due to its similar cetane number to gasoline, allowing for a focus on the fuel-bound oxygen content alone. G80B20_EHN5 is a mixture of gasoline, butanol, and 5% EHN. Adding butanol improves combustion with fuel-bound oxygen, resulting in a slightly higher peak pressure and earlier combustion phasing (Figure 5). The addition of butanol to the gasoline-EHN blend did not significantly affect LTHR levels. Figure 6 illustrates how butanol reduces HC, NOx, and smoke emissions. This highlights the impact of fuel-bound oxygen and butanol's higher latent heat of vaporization compared to gasoline.

Adding butanol improves brake thermal efficiency by enhancing combustion with oxygen from the fuel. Table 7 shows that adding oxygenated butanol to G100EHN_5 (G80B20_EHN_5) increases upper load range but decreases low load range due to butanol's higher latent heat of vaporization.

To investigate the impact of volatility on PFI-HCCI, diesel and Karanja biodiesel were blended with high-volatility gasoline. The gasoline-diesel blend, G80D20 Karanja biodiesel, an oxygenated fuel with a higher cetane number and lower volatility than diesel, has a cetane number comparable to G100EHN 2.5. This fuel combination helps to understand the impact of volatility. Figure 5 shows that high viscous fuels, G80D20 and G80K20, have lower peak pressure and longer ignition delay than G100_EHN 2.5. Despite having a higher cetane number and fuel-bound oxygen, G80K20 produces lower peak pressure and a longer ignition delay than G80D20. G80K20 fuel has lower volatility and delays low-temperature heat release (LTHR) when compared to G80D20. Figure 6 illustrates emission and BTE trends. Reduced BTE results in higher HC and smoke emissions, indicating poor combustion with low-volatile fuels. Poor combustion negatively impacts the engine's operable load range Optimal fuel volatility is crucial for efficient HCCI operation.

In summary, pressure, HRR, and emission trends indicate that increasing the cetane number of gasoline using EHN (25-33) and oxygenated butanol improves combustion by lowering HC emissions and increasing BTE. Additionally, blends with lower volatility than gasoline produced poor combustion. Gasoline with 5% EHN (G100EHN5) outperforms other fuel blends in terms of maximum operable load range and BTE and HC emissions.



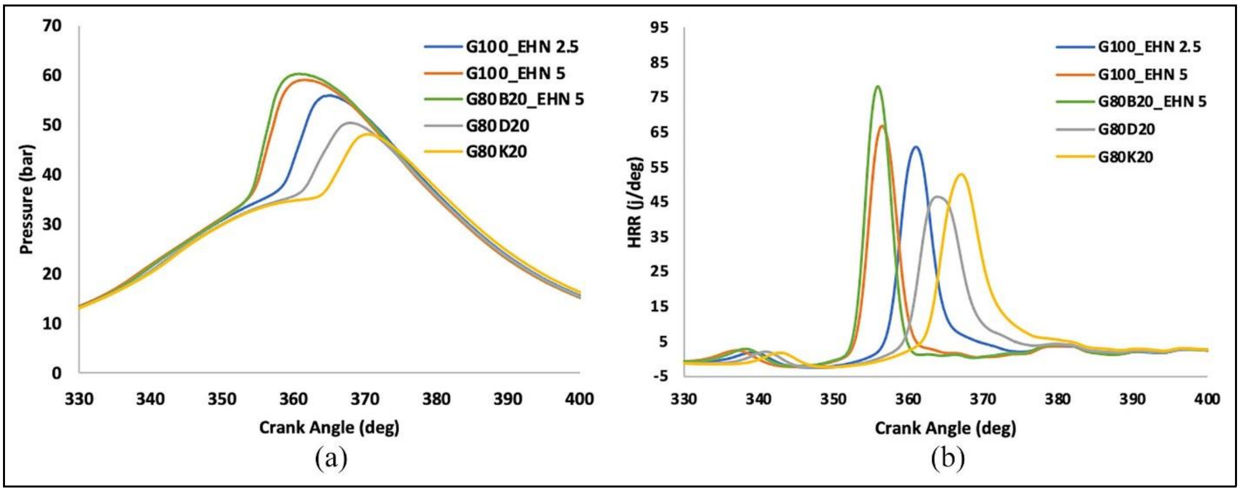


Figure 5. Comparison of pressure (a) and HRR (b) profiles with alternative fuels in PFI-HCCI mode at 60% load condition.

Table 4. Operational load range (highlighted in green) with alternative fuels in PFI-HCCI combustion mode along with CDC.

Strategy	Fuel/ Load	20%	30%	40%	50%	60%	70%	80%

Figure 6. Comparison of exhaust emissions and BTE (in log scale) with alternative fuels in PFI-HCCI mode at 60% load condition.

4.2.2 PCCI/ early DI operation with alternative fuels:

PCCI is an LTC mode that achieves low-temperature combustion by advancing fuel injection timing and using EGR.
PCCI-type lowtemperature combustion can operate at low loads, but achieving higher loads is challenging. This study examines the impact of cetane number and oxygenated alternative fuels on operating load range and emissions in early direct injection (DI)

compression ignition mode:

High volatile and low reactive gasoline and butanol are blended with diesel at 10% and 20% by volume, respectively. Alternative fuels for early DI and PCCI modes are chosen for their high volatility and low reactivity, resulting in longer fuel-air mixing time and delayed ignition, while avoiding early ignition and higher pressure rise rates. The nomenclature used for investigated alternative fuels is D90B10 (diesel 90% with butanol 10%) and D90G10 (diesel 90% with gasoline 10%), with similar terminology used for 20% fuel blends. The study examines early DI combustion with neat diesel and alternative fuels at 60% load (3.18 bar BMEP), 40% EGR, and 40 CA bTDC injection timing. Figures 7(a) and (b) show pressure and HRR profiles for tested fuels. Adding low reactive fuels like gasoline and butanol to diesel results in delayed ignition, phasing, and lower maximum pressure, as shown in Figure 7(a). Figure 7(b) shows similar trends for peak HRR occurrence and LTHR.
Blending gasoline and butanol in diesel reduces fuel reactivity compared to using it neat.

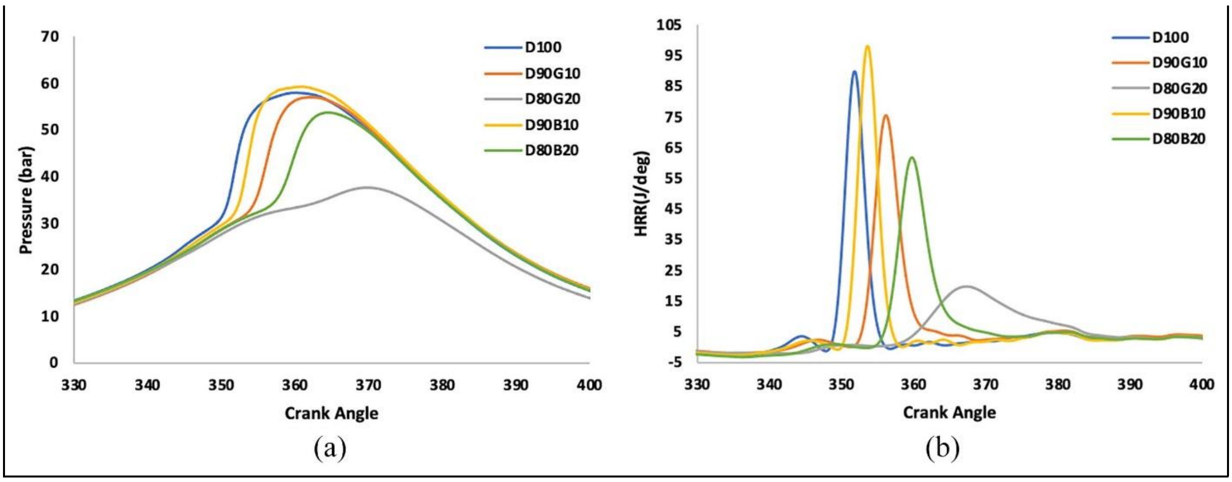


Figure 7. Comparison of pressure (a) and HRR (b) profiles with alternative fuels in PCCI mode at 60% load condition.

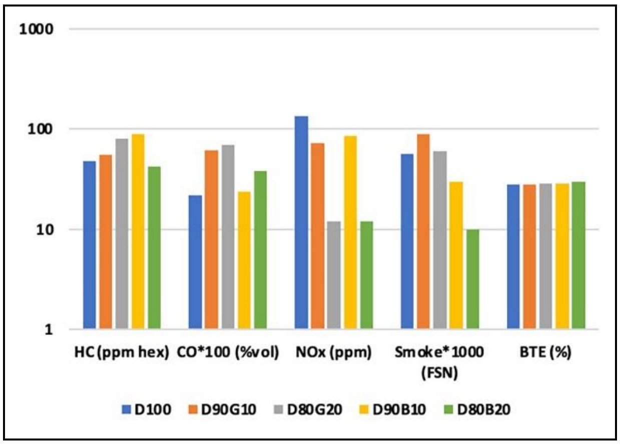


Figure 8. Comparison of exhaust emissions and BTE (in log scale) with alternative fuels in PCCI mode at 60% load condition.

Table 5 . Operational load range (highlighted in green) with alternative fuels in PCCI combustion mode along with CDC.

Strategy	Fuel/ Load	20%	30%	40%	50%	60%	70%	80%
Conventional Diesel Combustion (CDC)	Diesel							
PCCI	Diesel/D100							
	D90B10							
	D80B20							
	D90G10							
	D80G20							

As seen from the emission

Figure 8 shows that blending butanol or gasoline with diesel improves fuel volatility and reduces NOx emissions.

However, this does not always result in lower HC and CO emissions. Optimizing fuel injection timing is crucial for early DI combustion due to the significant impact of delayed combustion phasing caused by lower fuel reactivity.
Figure 8 shows that the 20% butanol blend (D80B20) significantly reduces HC, CO, and NOx emissions while improving BTE. All tested fuels had smoke FSN values of less than 0.1. D80G20 reduces NOx emissions significantly, but produces higher smoke emissions than other fuels. The 20% butanol blend in diesel (D80B20) outperforms all other fuel blends.

The maximum operable load range is 3.18 bar BMEP or 60% load in early direct injection combustion mode. Table 8 shows that achieving a higher load range is challenging.
When comparing early DI combustion to tested alternative fuels at a higher operation load (60% load), only D80B20 demonstrated significantly lower NOx and smoke emissions, indicating a low-temperature combustion mode. Figure 8 shows that other fuels do not meet ultralow NOx and smoke emissions. Therefore, only D80B20 can achieve PCCI combustion at 60% load (Table 8). D80G20 reduces NOx emissions significantly, but still produces high smoke emissions.

4.2.3 RCCI operation with alternative fuels:

RCCI investigated alternative fuels for port-injected low-reactivity and direct-injected high-reactivity fuels to reduce high HC and CO emissions. The engine can operate across the load range in RCCI with all tested fuels. To test the effects of PFI and DI fuels, the engine's operating parameters are kept similar to the base RCCI condition, with gasoline as the PFI fuel and diesel as the DI fuel (G100/D100). To conduct the DI fuel sensitivity study, the PFI fuel injection quantity remains constant.

The base fuel (G100/D100) and DI alternative fuel quantities are adjusted to achieve the desired load condition, and vice versa for the PFI fuel sensitivity study. To study the effect of fuel-bound oxygen content and reactivity on HC and CO emission trends, RCCI port injection uses ethanol and butanol blends instead of gasoline. G80E20/D100 refers to 80% gasoline with 20% ethanol as a PFI fuel and diesel as a DI fuel.
Similarly, DI alternative fuels have been tested alongside gasoline as a PFI fuel. The study blends low-reactivity gasoline (G100/D80G20) and butanol (G100/D80B20) with diesel to examine the impact of increased volatility, lower cetane number, and fuel-bound oxygen content. Karanja Biodiesel has been Blended with diesel (G100/D80K20) for DI fuel to assess the impact of using high-cetane fuel. diesel. The results are compared to neat diesel at 4.25 bar BMEP, without EGR.

Figures 9(a) and (b) display pressure and HRR profiles for alternative fuels, while Figure 10 displays engine performance and emissions on a log scale.
Figure 9(a) and (b) compare butanol and ethanol blends to gasoline as PFI alternative fuels. In comparison to base fuel (G100/D100), gasoline-butanol (G80B20/D100) and gasoline-ethanol (G80E20/D100) blends have lower peak pressure and delayed occurrence. Ethanol blends can significantly delay peak pressure and HRR. Figure 9(b) shows similar trends for peak HRR and LTHR. The gasoline-ethanol blend (G80E20/D100) misfires at high loads due to a higher proportion of premixed fuel.

Figure 10 shows that the gasoline-butanol (G80B20/D100) blend reduces HC and CO emissions due to its fuel-bound oxygen content in butanol. Adding butanol to gasoline at a 20% blend level increases the latent heat of vaporization and decreases the heating value. Butanol's high fuel-bound oxygen concentration may contribute to lower HC and CO emissions. Table 6 shows that ethanol has a higher cooling effect than butanol due to the difference in latent heat of vaporization between the two. This is evident in the emission plots, resulting in higher HC and CO levels and lower NOx Emissions from the ethanol blend. The ethanol blend reduces BTE, while the gasoline-butanol blend benefits from fuel-bound oxygen for better combustion and BTE.

The RCCI DI fuel study blends oxygenated alternative fuels (butanol, biodiesel, and high-volatile gasoline) with diesel at a 20% volume ratio. The CRDI fuel injection system imposed lubricity and viscosity constraints, resulting in lower blend levels. Butanol and gasoline exhibit higher volatility and lower reactivity than the reference diesel fuel, while Karanja biodiesel exhibits lower volatility and higher reactivity. This study examines how fuel volatility, reactivity, and oxygen content affect the potential for reducing HC and CO emissions through RCCI combustion.

low reactivity butanol-diesel (G100/D80B20) and gasoline-diesel (G100/D80G20) blends cause delayed combustion phasing, resulting in lower peak pressures and HRR compared to high reactivity Karanja-diesel (G100/D80K20) blend and neat diesel (G100/D100). These trends are to be expected given that butanol and gasoline have lower reactivity. A higher reactivity blend of Karanja-diesel promotes early low-temperature heat release. Figure 10 shows a comparison of exhaust emissions and BTE for RCCI DI alternative fuels at 80% operating load. Both gasoline-diesel and butanol-diesel blends emit more HC and CO than diesel RCCI. Butanol and gasoline have lower reactivity, which causes delayed combustion, peak pressure, and HRR. Reduced in cylinder gas temperatures cause flame quenching, and
Significantly lower unburned emissions oxidation, resulting in higher HC emissions. Although gasoline-diesel and butanol-diesel blends emit more smoke, they are still significantly lower than traditional diesel combustion methods. Lower NOx emissions indicate lower in-cylinder temperatures. All LTC strategies have extremely low absolute NOx values (within a 10 ppm measurement error). The blend of high reactivity and low volatile Karanja biodiesel-diesel (G100/D80K20) reduces HC emissions and has a better BTE than diesel (G100/D100).
Improved combustion phasing, as well as higher pressure and temperature conditions, may result in faster oxidation of HC and CO emissions.
Karanja biodiesel contains fuel-bound oxygen, which improves ignition quality and reduces HC and CO emissions.

The study on HCCI, PCCI, and RCCI combustion strategies using alternative fuels aimed to address limited operational load ranges and increased HC and CO emissions. The engine can operate across the entire load range in RCCI, and oxygenated fuel blends effectively reduce HC and CO emissions. HCCI and PCCI modes resulted in a limited operating load range. HCCI's low load range is limited by misfire, while high-load operations are limited by knocking combustion. Variable cetane fuels, such as butanol, can increase the operable window while reducing HC and CO emissions. Blending high volatility and oxygenated alternative fuels with diesel increases load range and reduces HC and CO emissions. HCCI operation.

Among six alternative fuels, gasoline with 5% EHN (G100_EHN5) provides the highest operable load range for PFI-HCCI. PCCI testing with four different fuels shows that D80B20 has a higher operable load range and lower HC and CO emissions. RCCI investigated five alternative fuels, including two for PFI and three for DI fuel. Butanol-gasoline blend is the optimal PFI fuel, while Karanja biodiesel-diesel is the most effective DI fuel for reducing emissions and improving BTE. The following section compares HCCI, PCCI, and RCCI strategies to the best alternative fuels for lower costs Use higher load conditions to determine the optimal LTC strategy for improved engine performance and reduced exhaust emissions.

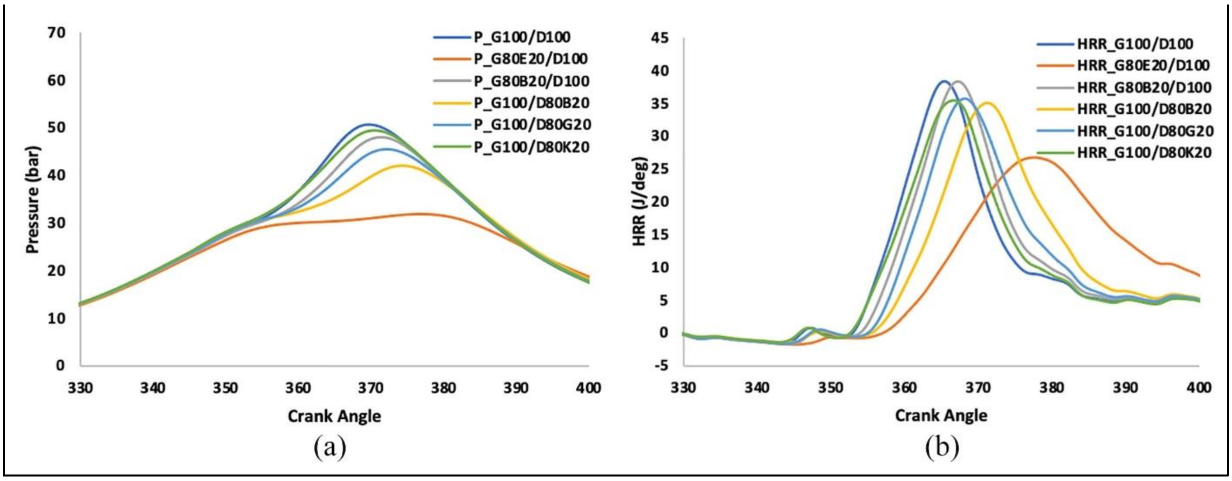


Figure 9. Comparison of pressure (a) and HRR (b) profiles with alternative fuels in RCCI mode at 80% load condition.

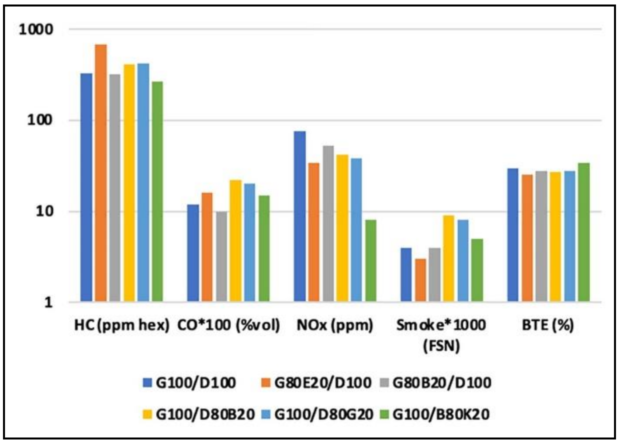


Figure 10. Comparison of exhaust emissions and BTE (in log scale) with alternative fuels in RCCI mode at 80% load condition.

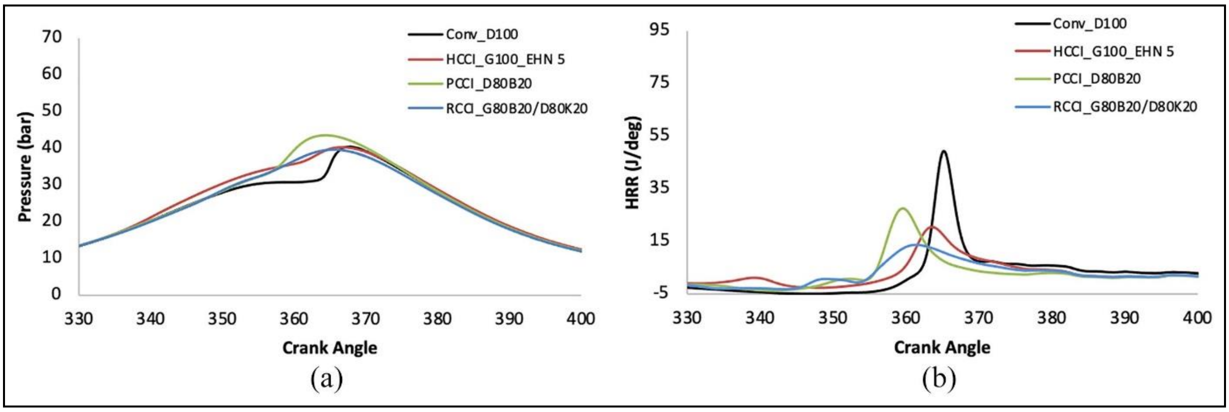


Figure 11. Pressure (a) and HRR (b) profiles of different LTC strategies operated with alternative fuels compared to conventional
combustion at 20% load conditions.

5.Conclusions:

This study compares HCCI, PCCI, and RCCI strategies using conventional and alternative fuels. First, the long-term care strategies are compared with Conventional diesel combustion employs a 40% load of diesel and gasoline. The LTC strategies are tested with alternative fuels to determine their operable load range and emission reduction potential. Finally, LTC strategies using alternative fuels are compared to conventional diesel combustion to assess engine performance and potential for emission reduction. The main findings from this study are as follows:

i. All three LTC strategies resulted in low NOx and smoke emissions, high unburned emissions, and higher thermal efficiencies than traditional combustion.

ii. Misfire limits HCCI's low-load operability. The high load is limited due to knocking combustion. PCCI operation at high loads is limited by knocking combustion. The RCCI strategy allows for a wider operating load range.

iii. The LTHR occurs first in the HCCI, followed by the RCCI and PCCI. LTHR occurs when charge homogeneity varies. HCCI is completely premixed, while RCCI is partially premixed and PCCI is least premixed due to in-cylinder injection and shorter fuel-air mixing time.

iv. Conventional combustion produces a steep pressure rise profile with a similar cetane fuel, while HCCI, PCCI, and RCCI combustion have smoother profiles at low loads. HCCI outperforms the other two LTC strategies for reducing HC and CO emissions. PCCI outperformed other LTC strategies in terms of BTE results.

v. Adding butanol and cetane improver to gasoline during HCCI operation reduces HC and CO emissions while improving brake thermal efficiency. Blending with low-volatility fuels instead of gasoline results in lower BTE and higher HC and CO emissions. Alternative fuels have high reactivity, fuel-bound oxygen content, and volatility, which improve HCCI combustion.

vi. In PCCI, blending low reactivity and high volatility fuels (e.g., gasoline and butanol) with diesel causes combustion delays. The D80B20 diesel butanol blend reduces HC, NOx, and smoke emissions, improves BTE, and increases CO emissions while extending engine operable load range.

vii. Using gasoline-butanol blends (G80B20/D100) as PFI in RCCI can reduce HC and CO emissions significantly. Ethanol's low fuel reactivity and high cooling effect delay combustion phasing significantly. Using a butanol-gasoline blend as PFI improved BTE by up to 2% at 60% load.
Using a Diesel-Karanja (G100/D80K20) blend as DI fuel in RCCI reduced HC and CO

emissions while improving BTE by up to 4% at 60% load. The study found that reactivity variations of DI fuel have a greater impact on combustion and emissions than volatility in RCCI combustion.
viii. When comparing LTC strategies with alternative fuels, prolonged combustion in RCCI results in lower BTE but higher HC and CO emissions at low loads. However, it contributes to a wider operable load range and improved BTE at higher loads.

ix. The study found that PCCI is best for low-load range operations, while RCCI is better for high-load operations due to its longer combustion time.

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