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Exploring Low-temperature Combustion Technologies for Enhanced Energy Efficiency and Sustainable Transportation

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ABSTRACT

As the automobile industry moves toward more sustainable solutions, improving energy efficiency and reducing internal combustion engine emissions have become increasingly important. Among emerging approaches, Low-temperature Combustion (LTC) strategies, including Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity-controlled Compression Ignition (RCCI), represent important developments for improving engine efficiency and reducing emissions. These technologies have the potential to meet increasingly stringent environmental standards while improving fuel economy. This review presents an in-depth analysis of LTC technologies, including their combustion processes, advantages, challenges, implementation methods, and comparative performance and emission characteristics. The review indicates that LTC technologies have significant potential to improve the efficiency of conventional internal combustion engines and reduce harmful emissions. In addition, future research directions are discussed, including advanced control systems, fuel development, and integration with hybrid powertrain systems. Overall, continued research and technological development are essential for realizing the potential of LTC technologies for energy-efficient and more sustainable transportation.

Keywords: Low Temperature Combustion; Emissions; Efficiency; Fuel flexibility; Environment.

1. INTRODUCTION

Low Temperature Combustion (LTC) technologies promise to meet stringent environmental regulations and improve fuel economy. hey identify several combustion processes sharing a characteristic of peak temperatures that are lower than those of conventional combustion. Reduction of temperature results in an extremely low emission of riders such as Nitrogen oxide (NOx) and Particulate matter (PM), which are two of the major pollutants in the conventional combustion processes (Soloiu *et al*. 2018). However, controlling the combustion process in a LTC engine is extremely difficult since the air-fuel mix must be precisely controlled along with its timing and cylinder conditions. The primary LTC strategies include HCCI (Homogeneous Charge Compression Ignition), PCCI (Premixed Charge Compression Ignition), and RCCI (Reactivity Controlled Compression Ignition), and each one functions through a different mechanism and offers diversified benefits.

Applications for LTC appear to be replete with promise when it comes to potential improvement of fuel economy and reductions of emissions for internal combustion engines. In addition, LTC strategies deliver better homogeneity in combustion, improved load matching, and thermal efficiency; thus, minimizing fuel consumption. However, close control over the combustion process is required; this, in turn, is based upon advanced control systems and techniques in sophisticated engine management.

2. HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE

2.1 Combustion Process in HCCI

In contrast to other engines, HCCI mixes the fuel-air prior to compression completely; hence, the whole mixture auto-ignites at the same time. This grants it higher thermal efficiency coupled with extremely suppressed emissions due to faster and better control of combustion processes. Full combustion takes place in such a manner that it ignites uniformly in the cylinder hence its emissions of NOx and PM are significantly lower as compared to conventional combustion methods. Fuels ranging from gasoline to diesel to alternative fuels are usable in HCCI engines, giving it good adaptability

concerning fuel selection. Such nature of homogeneous combustion promotes thermal efficiency making it one of the efficient combustion processes. The main contributing themselves to the high efficiency of HCCI engines is a rapid and complete combustion of the air-fuel mixture, which minimizes energy losses and maximizes the conversion of fuel energy into useful work. Lower peak temperature of the HCCI combustor leads to the decrease of NOx and PM emissions, giving rise to a cleaner burning process. The lower peak temperature of combustion in HCCI causes substantial diminution in the emission of NOx, one of the principal pollutants that lead to air pollution and smog formation. More complete combustion of the fuel decreases particulate matter formation and thus helps to improve the environmental benefits of HCCI engines. There is great flexibility with HCCI in terms of availability and cost of fuel. Since it can operate with many fuels, it is applicable in a wide range of uses. This fuel flexibility also allows the burning of low-carbon fuels, this directly translates to a severe reduction of greenhouse gas emissions.

2.2 Experimental Setup in HCCI Engine

The experimental setup for an HCCI engine involves a highly controlled environment in which one can make accurate observations of combustion behaviors. The engine enables the mixture of air and fuel to ignite. The combustion is based on low-temperature combustion, hence having less pollutants compared to a conventional internal combustion engine. The HCCI engine is a single-cylinder, and it is usually constructed with a comprehensive control setup for intake of air temperature, fuel injection timing, and EGR percentages, which can be quantified into several levels throughout the process. The experimental setup allows for a clean and highly controlled combustion process. Installation of pressure, temperature, and emissions sensors enables direct in situ measurements in "real-time" of the running of the engine and the controllable conditions (Shenawy *et al*. 2019). Availability of data acquisition at high speeds is through the core run analysis of combustion characteristics such as heat release rates, pressure profiles, and emissions. The knowledge acquired has been critical in assessing performance and efficiency in HCCI combustion for various operational conditions.

This is due to the entity involved in doing scientific experimentation involving HCCI techniques often involving exterior apparatus or apparatus in addition to the prime propelling apparatus, and this latter includes among things, items known as intake air heaters, a fuel conditioning systems and exhaust gas analyser. The intake air heater is the most important, considering that it enables the conditioning of the intake air to a suitable temperature, as this is essential in controlling and scheduling auto-ignition events in HCCI combustion. In this regard, the fuel conditioning system addresses factors related to delivered fuels' pressure and temperature while contributing to timing ignition and making combustion events repetitive and consistent. The exhaust gas analyser typically incorporates NDIR sensors and chemiluminescence analyser devices that are applied in the measurement of the concentrations of CO2, CO, NOx and unburnt hydrocarbons in the exhaust stream (Cheng *et al*. 2016). This provides valuable feedback regarding the combustion events and characterization of emissions from the engine. In combination, the experimental set-up provides researchers directions towards exploring fundamental aspects of HCCI combustion and offers pathways to improve engine performance while reducing impacts on the environment.

2.3 HCCI Airflow Strategies

Air flow strategy is important in HCCI engines to achieve an air-fuel mixture that is uniform and also to control auto-ignition. A fundamental part of HCCI operation is the intake air temperature and pressure control such that the charge reaches optimal auto-ignition conditions without knocking or pre-ignition. Variable valve timing (VVT) is used generally to alter both intake and exhaust valve timing in controlling the amount of air charge into the combustion chamber, as well as its timing of charge (Murugesa and Anand, 2018). Exhaust gas recirculation is also an effective way to control in-cylinder temperatures and reduce NOx emissions by reintroducing some of the exhaust gas back into the intake stream to dilute the charge and delay combustion.

2.4 Chemical Kinetics in HCCI Engines

The driving combustion reaction inside HCCI engines relies on the auto-ignition of a pre-mixed charge of air and fuel. The chemical kinetics involved in HCCI are complex in nature, but the auto-ignition is nearly simultaneous throughout the combustion chamber. The auto-ignition timing is sensitive to the chemical properties of the fuel, especially the octane number of the fuel directly impacting ignition delay (Shim *et al*. 2018). Such HCCI engines provide a unique challenge in controlling ignition delay to effect complete combustion and maximize fuel consumption. Rapid post-combustion heat release rate and resulting down-stroke combustion volume and pressure increase that accompanies auto-ignition of a whole charge can be an undesirable phenomenon and lead to engine knock, as well as reducing range of operation. Predictive and controllable operation among HCCI engines relies on advanced kinetic models that approximate reaction mechanisms.

2.5 Challenges in HCCI Engine

In HCCI operation, the temperature and pressure of in-cylinder are crucial. Intake air needs to be controlled by its temperature and pressure for the continuation of auto-ignition process. Techniques such as

EGR and VVT are used to control the temperature and pressure of intake air. If it is well controlled, it will provide stable combustion and reduce emissions. Proper control of the ignition process of an HCCI engine becomes extremely hard, hence more sophisticated control strategies are necessary (Krishnamoorthi *et al*. 2019). One of the limitations of HCCI engines is the narrow range of variables enabling stable combustion. Practical applications are limited because we cannot adjust these very small ranges without having sensors of advanced technology and control systems that can monitor and make adjustments in real time. One basic challenge to the use of HCCI engines is reliable ignition during cold starts. Advanced control strategies require real-time monitoring and sophisticated control systems for assured and stable HCCI combustion. Conditions related to HCCI ignition are sensitive to engine load and speed variations; hence, operation in a limited range is what HCCI engines allow. Extend operating range requires advanced control strategies and flexible design of the engine to extend the application of HCCI technology (Parthasarathy *et al*. 2021). The in-cylinder temperature required for cold-start HCCI ignition can be very high; hence, achieving this is critical for starting and operating efficiency during cold conditions. Designing advance pre-heating systems and control strategies to provide reliable and stable ignition during cold starts of the engines were required.

Real-time monitoring of advanced control systems is necessary to ensure that HCCI combustion remains steady over a wide spectrum of operational conditions. The option of ethanol or biodiesel fuels, namely, helps improve this all-important aim of reducing greenhouse gas emissions and fostering the environmental viability of HCCI engines. The overall design and thermal management of the combustion chamber are bound to considerably enhance stabilization and increase the efficiency of HCCI combustion. The fuel choice comes out to be highly sensitive to the entire HCCI process; a higher-octane number would have a lower auto-ignition tendency. Such ignition engines can operate on a broad spectrum of fuels with each being either good or bad from just about any standpoint-the alternatives include gasoline, diesel, and biofuels. The chemical and physical properties of the fuel, namely, its volatility and cetane number, come very strongly into play when maintaining stable combustion in the HCCI process. It is extremely sensitive to the temperature and pressure environment inside the cylinder at the time of ignition while, thus, calling for highly controlled air-fuel mixture preparation and combustion timings.

3. PREMIXED CHARGE COMPRESSION IGNITION ENGINE

3.1 Combustion Process in PCCI

In PCCI, the partially premixed charge is compressed to the point of auto-ignition. The combustion phasing is controlled directly by direct injection. The method allows much more control over the combustion process and thus reduces the likelihood of knocking while widening the operational range. The two-stage combustion process in PCCI enhances the control over the ignition and combustion phases, leading to stable and efficient combustion. Direct injection in PCCI allows better control of the combustion process, improving performance and efficiency even further. Choice of fuel is a very important factor determining combustibility, emission, and efficiency in PCCI mode. Fairly reactive fuels should be chosen to balance the auto-ignition and the direct injection phases. This engine can operate on a wide number of fuels including conventional diesel, gasoline, and alternative fuels such as ethanol and biodiesel. A highly advanced control system is needed in order to time the injection in such a way as to achieve the best possible performance. Just like HCCI, these engines allow a flexible and stable combustion over a wider range of operating conditions and thus have reduced NOx and PM emissions, making them environmentally friendly machines. In PCCI, lower peak combustion temperatures reduce the formation of NOx, and higher combustion efficiency reduces the formation of particulate matter. They operate across a wider range of conditions, compared with HCCI, enabling stable operation under a variety of engine loads and speeds and thus media applicability in PCCI technology.

3.2 Experimental Setup in PCCI Engine

For the study of a PCCI engine, an advanced arrangement of controlling combustion is typically part of an experimental setup, which is a combination of HCCI and standard diesel combustion. A PCCI engine will work through partial premixing of the fuel with air before the compression ignition allows combustion to be established at times predetermined by the operating parameters and can also enable the combustion to last for quite long periods to reduce soot and NOx emissions. Most experimental rigs consist of a single-cylinder engine equipped with electronic fuel injection for setting fuel timing, delivery pressure, and mass from an injected premix. This research engine is also provided with intake air control to allow regulation of air temperature and pressure into the combustion chamber, which is essential for meeting optimum combustion conditions for PCCI operation. The in-cylinder pressure, heat release rates, and several other parameters during combustion would be measured in real time through fast data acquisition systems and develop a broad overview of engine performance and emissions during various load conditions.

In addition to the standard components of the experimental setup, however, there might be some sophisticated parts of the experimental arrangement, like optical access to the combustion chamber to visualize the combustion. Typically, optical access is obtained using a

quartz window set in the cylinder head, which allows visualizing the combustion events using high-speed cameras and laser diagnostics that can capture the delivery and combustion in real time. Apart from that, exhaust gas analyzers are also set up to measure the concentration of emissions such as NOx, CO, CO_2, and unburnt hydrocarbons, providing valuable information about the environmental impact of the engine (Yoon *et al*. 2018). The experimental setup may also incorporate exhaust gas recirculation. An exhaust gas recirculation knife is one of the important items in the PCCI setup as it determines the temperature within the combustion chamber and helps in the reduction of the NOx emissions. Coming together, these units create an engine test setup intended for systematic investigation of the PCCI combustion. They allow optimizing of performance parameters without respect to the negative modes of emissions eliminated by PCCI combustion.

3.3 PCCI Airflow Strategies

Calibration of PCCI engine requires a delicate trade-off between premixing and stratification of the fuel-air mixture by optimized intake air charge, along with controls of the fuel injection. EGR is critical in the control of the combustion temperature as it has improved ignition delay, which is beneficial for an almost homogeneous combustion with low emissions in PCCI engines (Stefano *et al*. 2016). Turbocharging is often used to enhance air-fuel mixing by raising the density of air in order to effect mixing before ignition. Advanced intake air management systems include variable geometry turbochargers that can dynamically change air intake conditions for optimal combustion at different loads and speeds.

3.4 Chemical Kinetics in PCCI Engine

The PCCI engines run premixed, but with fuel injected instead earlier in the compression stroke than in conventional diesel engines. There is an increased opportunity for fuel and air to mix before auto-ignition. Chemical kinetics for PCCI plays a very important role in controlling ignition timing and combustion duration (Pandey *et al.* 2019). Since fuel injection happens early, significant reliance is required on low-temperature chemistry in order to achieve the initiation of combustion. The chemistry must be governed so that premature ignition is prevented without causing uneven combustion, thus forming less soot and reducing the formation of NOx emissions. Kinetic models that predict the occurrence of low-temperature reactions as well as high-temperature reactions are used to optimize combustion in PCCI engines.

3.5 Challenges in PCCI Engine

The precise control of injection timing and fuel mixture within PCCI is extremely complex, requiring at least highly advanced engine management systems to attain combustion stabilization and high efficiency. Advanced fuel injection systems and control strategies are the main factors that complicate and increase the cost of special design and manufacturing processes of PCCI engines. It consists of a two-stage combustion in which the fuel first undergoes compression prior to a portion that is injected directly into the combustion chamber (Pandey *et al.* 2018). It allows for improved control of the timing of combustion, hence permitting stable and efficient combustion. The combustion timing is optimized during direct injection, which reduces the possible tendency of knocking. Use of renewable fuels like ethanol and biodiesel give bigger environment benefits to PCCI engines with reduced greenhouse emission. Proper injection strategies remain very critical to the better functioning of a PCCI powertrain. Controls for optimal combustion will then occur with the enhancing of accurate inject timing with optimized quantity of fuel for the phases of premixing and also of direct injection.

Advanced fuel-injection systems, including high-pressure common rail and piezoelectric injector, provide flexibility in adjusting injection parameters according to engine load and speed, thus enhancing stabilization and efficiency in PCCI combustion (Nibin, *et al*. 2020). The integration of these systems with advanced control algorithms and real-time monitoring makes them optimize injection strategies and enhance the engine's functioning.

4. REACTIVITY CONTROLLED COMPRESSION IGNITION ENGINE

4.1 Combustion Process in RCCI

The RCCI uses two different fuels with different reactivities to provide a controlled combustion process. This is achieved by premixing a low-reactivity fuel with air and then directly injecting a high-reactivity fuel into the combustion chamber. The high-reactivity fuel ignites systematically, initiating combustion in the premixed charge, allowing for staged combustion and precise control over combustion timing and duration. The dual fuels with different reactivities in an RCCI engine offer significant flexibility and control over the ignition and combustion processes, thus ensuring increased efficiency and reduced emissions (Wategave *et al*. 2021). The operations in RCCI engines allow for flexible and stable combustion over a broad range of conditions, thus improving engine performance. These engines have high thermal efficiency due to better combustion control, which maximizes the conversion of fuel energy into useful work. Lower peak temperature in RCCI does reduce NOx and PM emissions, and this leads to cleaner combustion (Pan *et al*. 2017). The combustion will be better with maximum combustion completeness as well as the control using the dual fuels with different reactivities.

4.2 Experimental Setup in RCCI Engine

The experimental setup is designed to take advantage of a well-controlled dual-fuel RCCI combustion. In this dual-fuel configuration, two injections with different reactivities are added to the combustion chamber. The engine injects into the combustion chamber two fuels differing in their level of reactivity, such as a high reactivity fuel of diesel and low reactivity fuels of gasoline or natural gas. This dual-fuel strategy provides greater control over the phasing of combustion and reduces both NOx and soot emissions. In the experiments, a research engine with one cylinder is largely equipped with advanced dual-fuel injection systems like in (Senthil *et al.* 2019). This would allow the independence of controlling both the timing and quantity of the two different fuels injected in separate ways for maximizing the stratification of reactivity within the cylinder. The engine setup incorporates sensors to measure in-cylinder pressure, temperature, and other vital parameters along with a high-speed data acquisition system to capture the rapid changes during combustion.

In addition to the engine and fuel injection system, the RCCI experimental apparatus typically includes a control system that adjusts the air intake temperature and pressure. Intake air has to be appropriately conditioned to accomplish the desired thermal conditions that can influence fuel reactivity and the timing of combustion (Li *et al*. 2020). Further, exhaust gas analyzers are used in the setup to measure the NOx, CO, CO2, and unburnt hydrocarbons, giving a vital indication of the environmental performance of the engine. Optical diagnostics, including high-speed cameras and laser-based techniques, can also be used to visualize the combustion process in real-time, thereby giving insight into the spatial and temporal development of the flame. Setup can also include EGR systems in modulation of oxygen concentration and combustion temperature control for further reduction of NOx emissions. The complex interactions between dual fuels are thus the basis of the experimentation within this comprehensive setup, optimizing performance while reducing harmful emissions.

4.3 RCCI Airflow Strategies

The RCCI engines work on a dual-fuel principle at different reactivities, which calls for a unique airflow management scheme to control stratified fuel delivery and combustion phasing (Armin *et al*. 2021). The EGR is widely used in RCCI engines to regulate in-cylinder oxygen concentration and temperature, which in turn affects the reactivity of the fuel and the combustion timing. Furthermore, the RCCI engines require the regulation of the intake air temperature and pressure to enhance the variability of heat release, thus ensuring that the high reactivity fuel burns uniformly and at the appropriate time with subsequent controlled burning of the lower reactivity fuel. Such engines are usually implemented with split injection strategies integrated with advanced airflow management to ensure optimal fuel stratification for efficient combustion with low emissions.

4.4 Chemical Kinetics in RCCI Engines

The RCCI engines use a dual-fuel strategy where two fuels with different reactivities are injected separately. Normally, a high reactivity fuel (diesel) is injected directly into the cylinder and a low reactivity fuel (gasoline or natural gas) is port injected. The combustion in the RCCI engine is complex due to the interaction between the different reactivity zones in the combustion chamber (Singh *et al.* 2020). The high reactivity fuel initiates the combustion event, whereas the low reactivity fuel determines the rate of heat released and ensures a smoother and more controlled combustion. Dual fueling allows for very high flexibility in how the combustion process is controlled, hence giving lower emissions and higher efficiency from combustion. To obtain optimal combustion conditions, kinetic models used within RCCI engines need to predict interactions between fuels as well as the respective ignition characteristics.

4.5 Challenges in RCCI Engine

The chemical composition of the fuels involved also poses challenges in dual-fuel operation in RCCI. It is a technology that requires compatible fuels and refueling infrastructure, thus limiting the practical applicability. Additionally, managing two independent fuel systems increases the complexity of engine design often calling for advanced control strategies. Integration of dual-fuel systems and advanced control algorithms with RCCI engines increases their complexity and cost. Calibration of fuel injection and mixture preparation is critical in RCCI engines, requiring advanced calibration techniques. The injection pattern in RCCI mode is complex, and the fuel mixture demands sophisticated engine management systems to ensure stable and efficient combustion. It is a dual-fuel strategy, often with low-reactivity fuel, such as gasoline, premixed with air and injected into the combustion chamber, while the high-reactivity fuel, typically diesel, is directly injected (Tayari and Abedi, 2019). The strategy ensures very fine control of the combustion process for maximum efficiency and minimum emissions. The staged ignition sequence ensures the effective regulation of the combustion duration and timing. For proper operation of RCCI, effective control strategies are required, where advanced control systems are used to manage both the timing and quantity of injection from premixed and direct injection. Techniques such as VVT and EGR are utilized to control in-cylinder conditions for sustained combustion. With their control strategy, optimal performance is established over a range of operating conditions for the engine. State-of-the-art sensing and

real-time monitoring systems further enhance control over the combustion process, improving overall RCCI performance and efficiency.

Table 1. Advantages and challenges in LTC technologies

Technology	Advantages	Challenges	Reference
HCCI	High efficiency, low emission, flexibility in fuels	Control complexity, Narrow operating range, Difficulties with cold start	Gawale and Srinivasulu, (2020)
PCCI	Better control, reduced emission	Extended operating range Injection timing, complexity	Wang *et al.* (2013)
RCCI	Better control with high efficiency and low emissions.	Fuel infra-structure, complexity, calibration.	Senthil *et al.* (2019)

5. COMPARATIVE ANALYSIS OF LTC TECHNOLOGIES

Although HCCI, PCCI, and RCCI all target low-temperature combustion, each of these technologies has distinct strengths and weaknesses. Comparing these technologies highlights their individual advantages and challenges, providing insight into their application fields and limitations. Table 1. represents the advantages and challenges in LTC technologies.

5.1 Fuels in HCCI, PCCI, and RCCI Engines

Fuels play a pivotal role in the performance and emissions characteristics of advanced combustion engines such as HCCI, PCCI, and RCCI. The HCCI engines typically utilize high-octane fuels like gasoline to control auto-ignition, though alternative fuels like ethanol, natural gas, and hydrogen are also explored for their potential to reduce emissions(Jain *et al.* 2017). Alternatively, PCCI engines, which rely on early fuel injection for better premixing, primarily use diesel but can benefit from biodiesel and various fuel blends to enhance combustion and reduce pollutants (Shukla *et al.* 2023). However, RCCI engines employ dual-fuel strategies, most commonly combining diesel with low-reactivity fuels such as gasoline or natural gas, allowing precise control over the combustion process, optimizing efficiency, and minimizing emissions. Each of these combustion modes demands specific fuel properties to achieve optimal performance, and the continued exploration of alternative fuels and blends is essential for advancing engine technology and meeting stringent emission standards (Chaudhari and Deshmukh, 2020). It focused on conventional compression ignition (CI) engines, their findings on emission reduction strategies offer valuable insights for similar efforts in LTC engines (Nemmour *et al.* 2023). It is demonstrated that using TiO_2 nano-additives with biodiesel can improve emission characteristics, while it was explored the effectiveness of a cost-effective Cu-Zn-coated catalytic converter in reducing emissions. These approaches can be adapted to the unique challenges of minimizing emissions in LTC systems.

5.2 Performance and Emission Testing

During testing of HCCI, PCCI, and RCCI engines, various performance and emissions trends have emerged due to their unique in-cylinder combustion processes and control strategies. Table 2 represents performance and emission metrics of LTC technologies.

Table 2. Performance and emission metrics of LTC technologies

Parameters	HCCI	PCCI	RCCI	Reference
Efficiency	High	High	Very High	Krishnamoorthi *et al.* (2019)
NOx Emissions	Very Low	Low	Very Low	Noh and No (2017)
PM Emissions	Very Low	Low	Very Low	Murugesa and Anand (2018)
CO Emissions	Moderate	Low	Low	Agarwal *et al.* (2021)
HC Emissions	High	Moderate	Low	Singh *et al.* (2020)

5.3 Heatmap Analysis

A heatmap analysis comparing HCCI, PCCI, and RCCI combustion technologies shows that RCCI has the highest efficiency and lowest emissions. While RCCI is highly efficient with much lower NO_x and PM emissions, HCCI is exhibits higher HC emissions, though efficient. The PCCI shows lower efficiency and slightly higher NO_x and PM emissions compared to RCCI, but it has lower CO emissions. Overall, RCCI stands out as the most efficient and cleanest among the three.

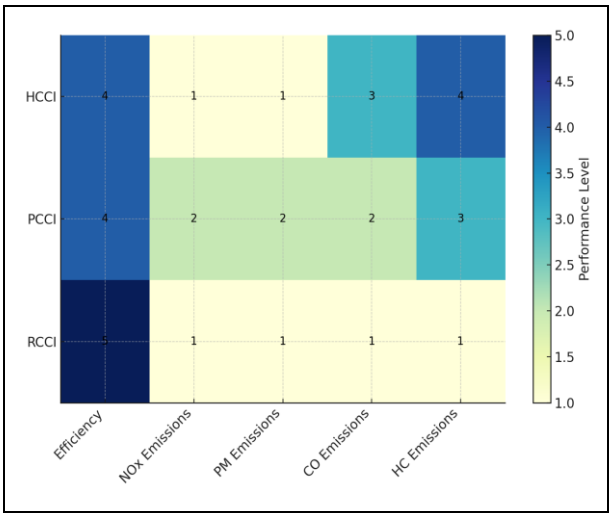


Fig. 1: Heatmap analysis of LTC engines

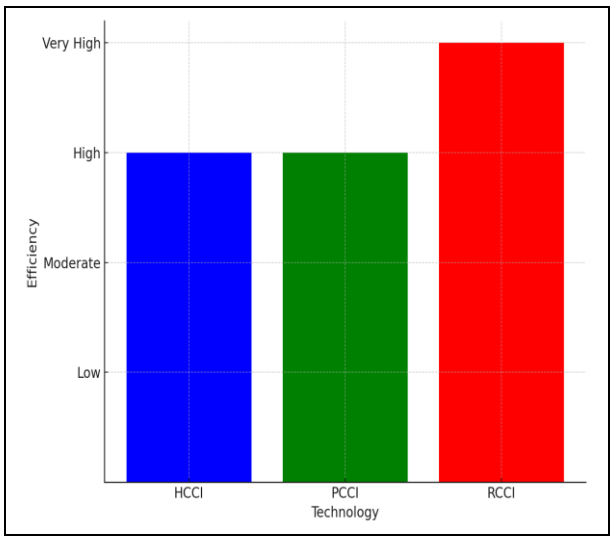


Fig. 2: Emission comparison of LTC engines

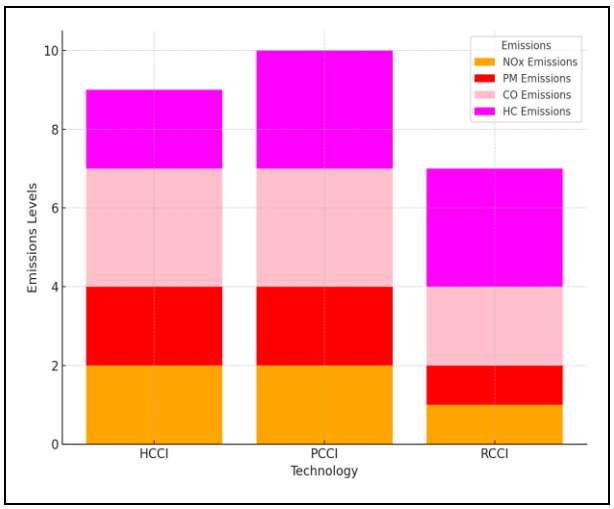


Fig. 3: Efficiency comparison of LTC engines

The HCCI mode provides high efficiency and low emissions but suffers from control complexity and a narrow operating range. The PCCI offers improved control and a wider operating range than HCCI but increases complexity due to the dual injection strategy. Good control and higher efficiency are provided by RCCI, but it demands a well-developed infrastructure and high calibration. An HCCI engine running on gasoline showed 15% higher thermal efficiency than a conventional spark–ignition engine, with NO_x emissions reduced by 90%. However, stable combustion was not achieved across variable loads, and cold starts remained problematic. In a PCCI engine using an ethanol-diesel blend, a 10% higher thermal efficiency was realized, with a significant reduction in NO_x and PM emissions compared to traditional diesel engines (Gowtham *et al.* 2019). Direct injection also eased the crevice volume situation by allowing more precise control of the combustion phases, though precise injection timing was required.

Fig. 1 represents the heatmap analysis of LTC engines. The efficiency of RCCI engines tested with a dual fuel of natural gas and diesel increased by about 20%, and NO_x and PM emissions were drastically reduced. This dual-fuel approach offered careful control over the combustion process, despite the challenges of a robust fuel infrastructure. Fig. 2 represents the emission comparison of LTC engines and Fig.3 represents the efficiency comparison of LTC engines. The various regimes in this graph show the region where soot and NO_x are formed, as well as their overlapping conditions.

The soot regions are the predominant condition for soot formation, the NO_x regions are the predominant condition for NO_x formation, and the overlapping regions describe the condition in which both are formed. Looking at the technology zones, RCCI, which is the blue zone, actually spans a very wide range of operating conditions, mostly avoiding high soot formation and overlapping partly with the NO_x region. The PCCI, represented by the orange zone, avoids the high soot region but is more prone to NO_x formation than RCCI. Fig. 4 represents the emission profiles of LTC engines.

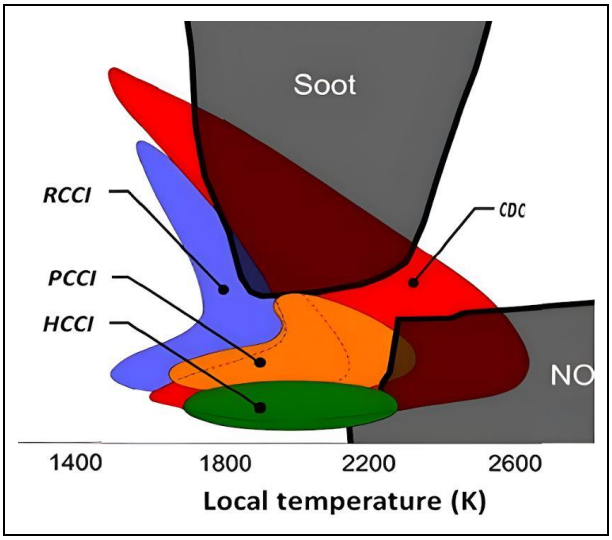


Fig. 4: Emission profile of LTC engine (Gwalwanshi *et al.* 2023)

In HCCI, the green zone runs in low temperature and low equivalence ratio, resistant to the formation of both soot and NO_x. Conventional diesel combustion shown in black/grey has quite a bit of overlap with both the soot and NO_x formation regions. Key insights from these experiments show that RCCI well manages emissions, staying mostly outside the high soot formation conditions and partially managing NO_x formation. In the case of PCCI, though very effective in avoiding soot formation, there is a higher tendency toward NO_x formation (Wang *et al.* 2015). The HCCI provides the best emission characteristics through combustion covering both zones of high soot and NO_x formation at lower temperatures and equivalence ratios, while

conventional diesel exhibited the highest levels for both soot and NO_x emissions, indicating poorer performance regarding environmental performance in comparison with advanced combustion technologies.

6. ADVANCED CONTROL SYSTEMS

Developing advanced control algorithms is necessary to manage the sophisticated combustion processes associated with LTC engines. Advanced control systems can further improve the performance and reliability of HCCI, PCCI, and RCCI engines. Integration with real-time monitoring and adaptive control strategies will also optimize the combustion process, enhancing efficiency and reducing emissions (Salahi and Gharehghani, 2019). Exploring alternative fuels and fuel blends is essential for improving the performance and reducing emissions associated with LTC engines. New fuels could also be developed for LTC applications, with ongoing research in this area. Additionally, the environmental benefits of LTC technologies can be enhanced with the development of renewable and low-carbon fuels, reducing greenhouse gas emissions. Integrating LTC engines with hybrid powertrains can further leverage the relative benefits of the two technologies. Hybrid systems could optimize the operation of LTC engines leading to further improvements in fuel efficiency and emissions through the electric powertrain. The combination of LTC and hybrid technologies may increase overall performance and environmental benefits, offering a sustainable solution for future transportation needs.

7. AI-DRIVEN CONTROL METHODS FOR ENGINE OPTIMIZATION

It was demonstrating the revolutionary power of AI-driven approaches for optimizing engine control in Low-Temperature Combustion (LTC) systems. Demonstrated how neural networks can be utilized to forecast and change important combustion parameters in real time, hence enhancing fuel efficiency and pollution control in LTC engines by addressing nonlinear dynamics (Zhang *et al*. 2016). It was focused on Model-Based Predictive Control (MPC) for managing complex combustion in HCCI engines, implying that AI enhancements, particularly machine learning, could improve predictive models' accuracy and adaptability.

8. CONCLUSION

Technologies such as HCCI, PCCI, and RCCI represent key milestones in the evolution of internal combustion engines, offering tremendous efficiency gains and significantly reduced emissions. These LTC techniques are expected to play an important role in the future of automotive applications, supporting the industry's push for more sustainable and energy-efficient solutions(Ma *et al*. 2021). Despite their promise, several technological hurdles remain, including issues with combustion control, fuel compatibility, and scalability for mass-production (Vinodkumar and Karthikeyan, 2022). Addressing these challenges through ongoing research and development will be critical to realizing the full potential of LTC technology. By overcoming these obstacles, the automobile industry can continue to innovate, creating engines that meet the needs of modern transportation while minimizing environmental impact. Thus, LTC technologies hold significant promise for revolutionizing internal combustion, marking a crucial step forward in sustainable automotive engineering.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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