World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Advanced combustion strategies for improving ic engine efficiency and emissions

BHASKARA *

Department of Automobile Engineering, Government polytechnic Kushalnagar, Karnataka, India.

World Journal of Advanced Research and Reviews, 2023, 17(02), 905–916

Publication history: Received on 27 November 2022; revised on 18 February 2023; accepted on 22 February 2023

Article DOI: https://doi.org/10.30574/wjarr.2023.17.2.1444

Abstract

The growing need for higher fuel efficiency and compliance with increasingly stringent emission regulations has prompted significant advancements in internal combustion (IC) engine technology. Traditional combustion methods, while widely utilized, face inherent challenges such as limited thermal efficiency and the production of harmful emissions like nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC). To address these concerns, researchers and engineers have developed a range of advanced combustion strategies that offer the potential to drastically improve engine efficiency while minimizing environmental impact.This paper provides a comprehensive analysis of cutting-edge combustion techniques, with a focus on strategies that balance the trade-off between fuel efficiency and emission reduction. Prominent among these strategies is Homogeneous Charge Compression Ignition (HCCI), which utilizes a lean, premixed air-fuel mixture to achieve spontaneous ignition at low temperatures, significantly reducing NOx and PM emissions. Another promising technique, Reactivity-Controlled Compression Ignition (RCCI), leverages the controlled use of two fuels with different reactivity levels, enabling precise control over the combustion process and enhancing both fuel efficiency and emission control. In contrast, Gasoline Direct Injection (GDI) technology improves fuel atomization and combustion control by injecting fuel directly into the combustion chamber, leading to higher efficiency and power output, albeit with challenges related to particulate emissions.In addition to these combustion strategies, this paper explores the role of Low-Temperature Combustion (LTC), which operates at reduced in-cylinder temperatures to mitigate the formation of NOx and soot, as well as the potential of advanced ignition systems like plasma or laser-based ignition to improve lean-burn combustion processes. Furthermore, the paper examines the integration of renewable fuels, such as hydrogen and biofuels, with advanced combustion techniques to support the global transition toward cleaner energy.The analysis also considers technological enablers such as variable valve timing (VVT), turbocharging, and sophisticated exhaust after-treatment systems that complement these advanced combustion strategies. Moreover, the application of simulation and optimization tools, including computational fluid dynamics (CFD) and machine learning (ML), is highlighted as essential for refining engine design and optimizing combustion processes.Despite the notable progress, challenges remain in terms of system complexity, control precision, and expanding the operational range of these advanced combustion techniques. As the automotive industry moves towards electrification and hybridization, advanced IC engine combustion strategies will continue to play a crucial role in improving vehicle performance and sustainability. This paper concludes by outlining the future prospects for further optimizing combustion efficiency and integrating renewable fuels in next-generation IC engines, thereby contributing to a cleaner, more efficient transportation sector.

Keywords: Advanced Combustion Strategies; Homogeneous Charge Compression Ignition (HCCI); Reactivity-Controlled Compression Ignition (RCCI); Gasoline Direct Injection (GDI); Low-Temperature Combustion (LTC); Engine Efficiency Emission Reduction

1 Introduction

Internal combustion (IC) engines have long been the cornerstone of transportation and power generation systems worldwide. Their ability to provide reliable and robust power at relatively low costs has made them indispensable

*Corresponding author: BHASKARA

across various sectors, including automotive, aerospace, and industrial machinery. Despite their widespread use, IC engines face significant challenges in terms of thermal efficiency and environmental sustainability. As global energy demands continue to rise and emissions regulations become increasingly stringent, there is growing pressure to enhance the performance of IC engines while minimizing their environmental impact[1].

Conventional IC engine designs, primarily based on spark ignition (SI) and compression ignition (CI) technologies, exhibit fundamental limitations. In SI engines, the air-fuel mixture is ignited by a spark plug, while in CI engines, the fuel is injected into compressed air, leading to spontaneous ignition. Both designs are widely used but are constrained by their inherent combustion processes. These traditional engines often operate at suboptimal thermodynamic efficiency due to combustion inefficiencies, such as incomplete fuel burning and heat losses. Consequently, they contribute to higher fuel consumption and significant emissions of pollutants like carbon dioxide (CO_2), nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC).

1.1 The Emission-Efficiency Trade-Off

One of the critical challenges in IC engine design is the trade-off between fuel efficiency and emissions. Conventional SI and CI engines operate at relatively high temperatures, which is necessary for efficient energy conversion. However, high combustion temperatures lead to the formation of NOx, a harmful pollutant contributing to air quality degradation and health issues. On the other hand, reducing combustion temperatures to curb NOx formation often results in incomplete combustion, producing higher levels of CO, HC, and PM, and leading to lower fuel efficiency.

The increasing focus on reducing greenhouse gas emissions, particularly CO_2, has also placed fuel consumption under scrutiny. Given that IC engines are responsible for a large share of global CO_2 emissions, improving thermal efficiency is essential to reducing the carbon footprint of transportation and power sectors. However, achieving this balance between low emissions and high efficiency has proven difficult using conventional combustion strategies.

1.2 The Need for Advanced Combustion Strategies

To meet the evolving demands for cleaner, more efficient engines, significant research has been dedicated to developing advanced combustion strategies. These strategies focus on modifying the traditional combustion process to reduce heat losses, minimize pollutant formation, and optimize fuel consumption. Some of the most promising approaches include:

- Homogeneous Charge Compression Ignition (HCCI): A strategy that combines features of both SI and CI engines, aiming for lean combustion with low temperatures to reduce NOx and PM emissions while improving thermal efficiency.
- Reactivity-Controlled Compression Ignition (RCCI): A technique involving the use of two fuels with different reactivity levels, which allows for greater control over the combustion process and results in improved efficiency and reduced emissions.
- Gasoline Direct Injection (GDI): This technology provides precise control over fuel injection timing and mixture formation, leading to improved atomization and more efficient combustion, though with challenges related to PM emissions.
- Low-Temperature Combustion (LTC): A combustion approach designed to keep in-cylinder temperatures low enough to minimize the formation of NOx and soot, while maximizing thermal efficiency.

These advanced combustion techniques represent a shift away from conventional designs toward more sophisticated, controlled combustion processes that aim to simultaneously improve fuel economy and emissions performance. Additionally, the integration of renewable fuels such as hydrogen, biofuels, and synthetic fuels into IC engines provides another avenue for reducing carbon emissions and promoting sustainability[2].

1.3 The Role of Regulatory Pressure and Technological Innovation

The development of advanced combustion strategies has been driven in part by regulatory pressure. Governments around the world are imposing stricter emissions standards, mandating that automakers and industries reduce CO_2 emissions and improve fuel efficiency across their fleets. Regulatory frameworks such as the European Union's Euro 7 standards and the U.S. Corporate Average Fuel Economy (CAFE) standards require significant reductions in pollutant emissions and fuel consumption, motivating research and innovation in engine design.

In parallel, technological advancements in areas such as variable valve timing (VVT), turbocharging, advanced ignition systems, and exhaust after-treatment systems have enabled more precise control over the combustion process. These technologies complement the advanced combustion strategies by allowing for greater flexibility in engine operation, leading to optimized performance across a wide range of driving conditions.

1.4 Paper Structure and Scope

This paper provides an in-depth exploration of various advanced combustion strategies for improving IC engine efficiency and reducing emissions. Section 2 discusses the challenges associated with conventional combustion methods, highlighting the limitations in thermal efficiency and emission control. Section 3 delves into advanced combustion strategies, including HCCI, RCCI, GDI, and LTC, examining their operational principles, benefits, and challenges. Section 4 explores enabling technologies such as VVT, turbocharging, and advanced ignition systems, which are critical for the implementation of these advanced strategies. Finally, Section 5 discusses future trends, the integration of renewable fuels, and the outlook for further innovations in IC engine technology.

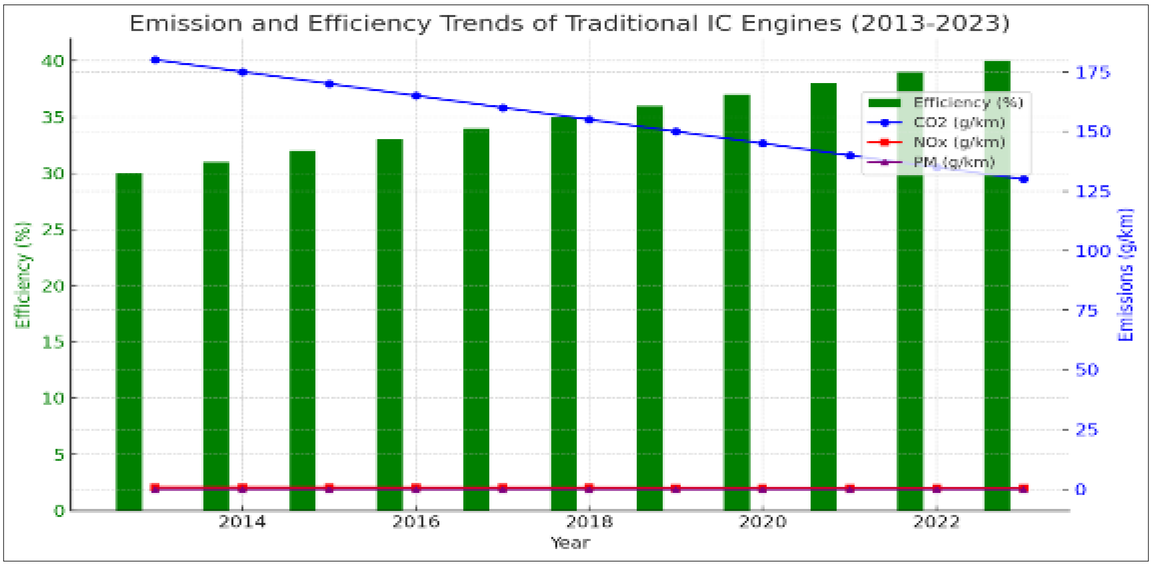

Figure 1 Emission and efficiency trends of traditional IC engines over the last decade

2 Conventional Combustion Challenges

Internal combustion (IC) engines have long been the primary technology for power generation and transportation. However, despite their widespread use, conventional combustion strategies in spark ignition (SI) and compression ignition (CI) engines are subject to several inherent limitations that affect both their thermal efficiency and environmental impact. This section explores the key challenges associated with traditional combustion methods[3].

2.1 Thermodynamic Limits

One of the fundamental challenges in conventional combustion engines arises from the thermodynamic constraints, particularly the Carnot efficiency. The Carnot efficiency represents the theoretical maximum efficiency that any heat engine can achieve, which is dependent on the temperature difference between the combustion chamber and the environment. In real-world engines, the efficiency is much lower than the Carnot limit due to various losses, including heat transfer, friction, and incomplete combustion.

- Maximum Pressure Rise Rate (MPRR): The MPRR also imposes limitations on combustion efficiency. In SI and CI engines, high-pressure combustion is needed to achieve efficient energy conversion, but this leads to increased mechanical stress on engine components. Consequently, there is a trade-off between maximizing efficiency and ensuring durability and reliability of the engine.

In both SI and CI engines, the combustion process often occurs too rapidly or unevenly, resulting in high peak pressures that lead to mechanical stress and reduced engine life. To manage these issues, engines are typically designed to operate at less than optimal combustion conditions, compromising thermal efficiency.

2.2 Emission Concerns

Conventional IC engines are major contributors to air pollution due to the emissions generated during the combustion process. Different types of emissions are produced in both SI and CI engines, posing significant environmental and regulatory challenges[4].

- Spark Ignition (SI) Engines: In SI engines, the air-fuel mixture is ignited using a spark plug, which typically results in incomplete combustion, especially at low or fluctuating engine loads. This incomplete combustion generates high levels of carbon monoxide (CO) and unburned hydrocarbons (HC). Additionally, SI engines operate at high combustion temperatures, which promote the formation of nitrogen oxides (NOx), a major contributor to smog and respiratory problems.
- Compression Ignition (CI) Engines: CI engines, commonly used in diesel applications, inject fuel into compressed air, leading to spontaneous ignition. While CI engines are generally more fuel-efficient than SI engines, they produce higher levels of particulate matter (PM) and NOx emissions. The formation of particulate matter is a direct result of the non-uniform combustion and fuel-air mixing, leading to soot particles that can harm both the environment and human health.

Regulatory standards, such as the Euro 6 and Tier 3 emission regulations, impose strict limits on these emissions, pushing engine developers to find new ways to control or eliminate these pollutants. However, conventional SI and CI engines, without the use of advanced after-treatment systems or combustion strategies, struggle to meet these stringent requirements while maintaining high performance and fuel efficiency.

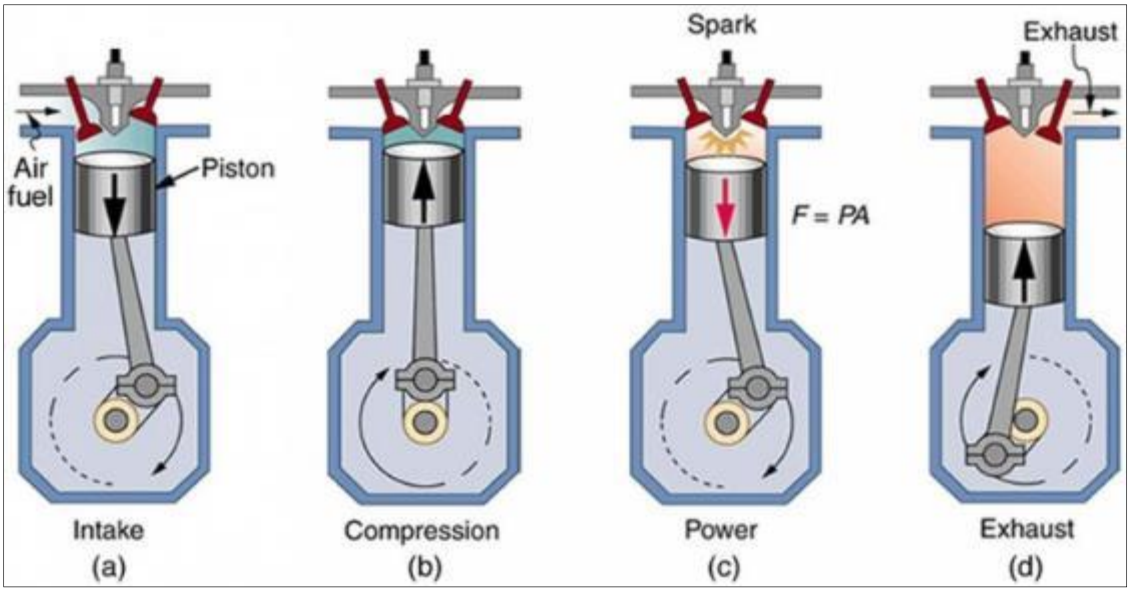

Figure 2 Typical combustion cycle of SI and CI engines

3 Advanced Combustion Strategies

Advanced combustion strategies are designed to address the limitations of conventional internal combustion (IC) engines, such as low thermal efficiency and high pollutant emissions. This section presents some of the most promising techniques that aim to improve engine efficiency while minimizing harmful emissions[5].

3.1 Homogeneous Charge Compression Ignition (HCCI)

Homogeneous Charge Compression Ignition (HCCI) is a combustion technique that combines elements of both spark ignition (SI) and compression ignition (CI) engines. In HCCI, a homogeneous mixture of air and fuel is compressed to the point of auto-ignition without the use of a spark plug or direct fuel injection. The auto-ignition occurs simultaneously throughout the combustion chamber, leading to a more uniform burn and lower combustion temperatures compared to traditional SI and CI methods.

- Advantages: The lower combustion temperature in HCCI significantly reduces the formation of nitrogen oxides (NOx) and particulate matter (PM), while also improving thermal efficiency.
- Challenges: Controlling the timing of auto-ignition is difficult because it depends heavily on in-cylinder temperature and pressure. This limits the operating range of HCCI, particularly under high-load or transient conditions. Furthermore, achieving stable combustion across varying engine speeds and loads remains a challenge.

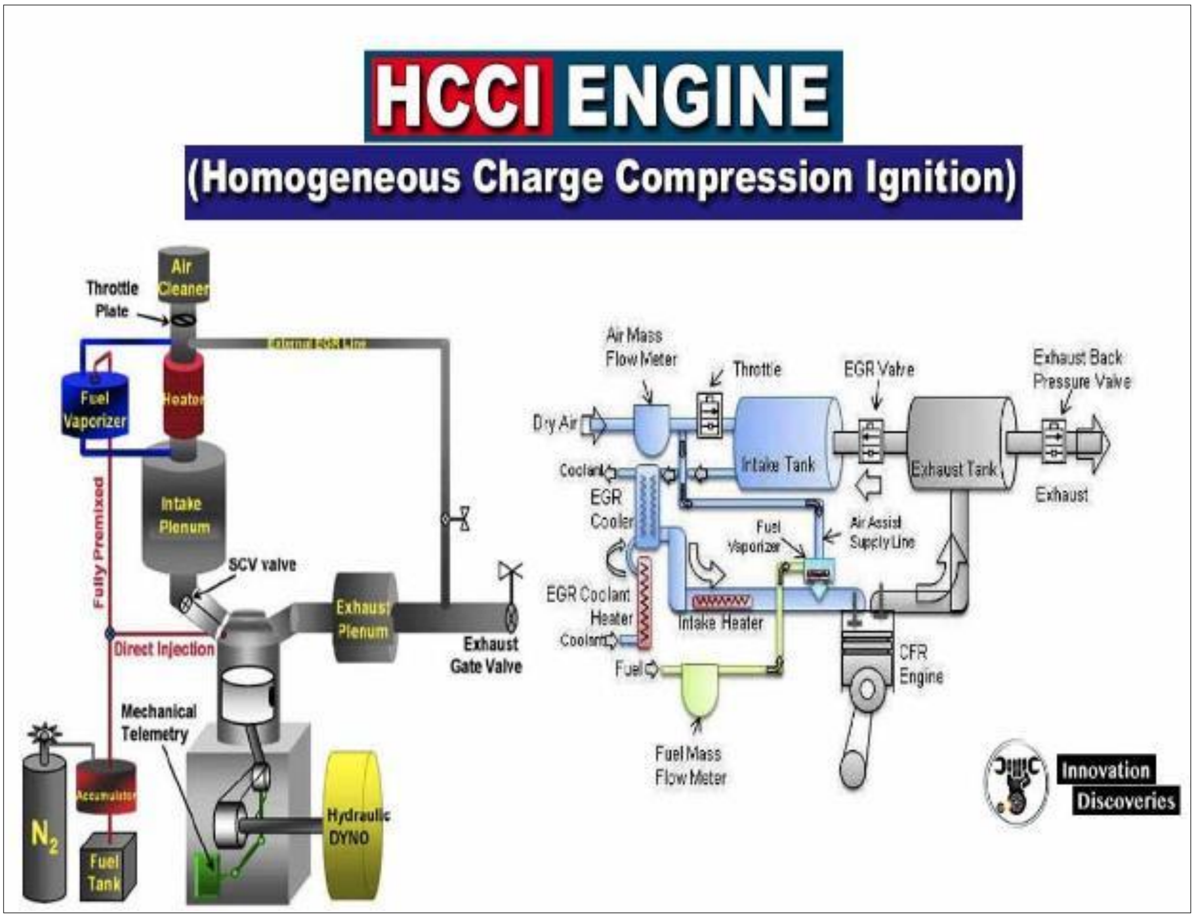

Figure 3 Schematic of HCCI combustion

3.2 Reactivity-Controlled Compression Ignition (RCCI)

Reactivity-Controlled Compression Ignition (RCCI) is a more advanced variation of HCCI that involves the use of two fuels with different reactivity levels, typically a highly reactive fuel (e.g., diesel) and a less reactive fuel (e.g., gasoline or natural gas). The two fuels are injected separately into the cylinder, enabling more precise control over the combustion process by varying the proportion and timing of the fuels.

- Advantages: RCCI offers improved control over combustion, leading to better fuel economy and lower emissions. It can achieve a high thermal efficiency while reducing the production of NOx and PM. RCCI also minimizes the occurrence of engine knock, a common issue in SI engines.
- Challenges: RCCI requires a dual-fuel system and complex fuel injection strategies, making it more challenging to implement in commercial applications. Furthermore, optimizing the fuel ratio and injection timing across different load and speed conditions is complex.

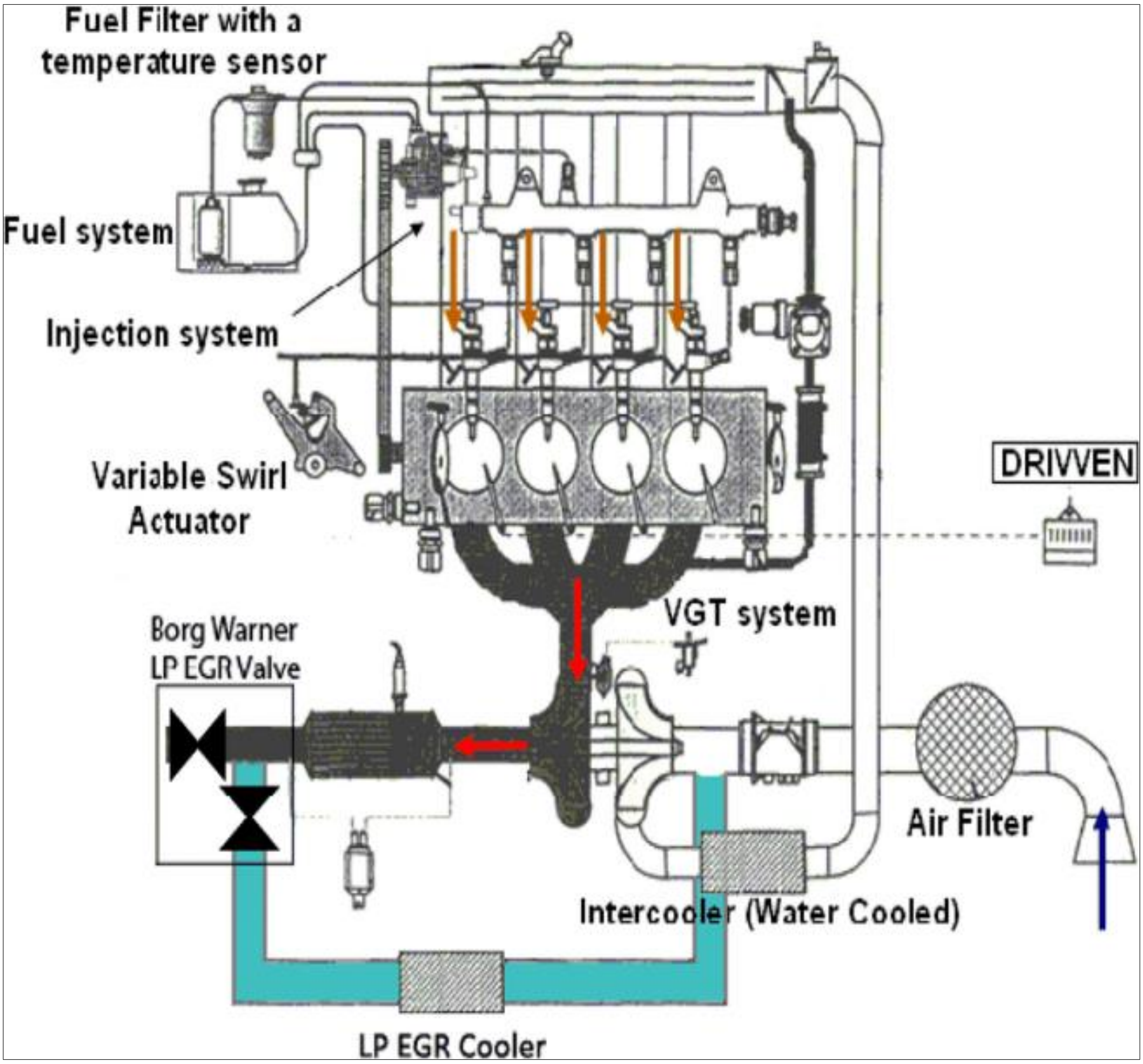

Figure 4 Schematic of RCCI combustion

3.3 Gasoline Direct Injection (GDI)

Gasoline Direct Injection (GDI) is a technology that allows gasoline to be injected directly into the combustion chamber, as opposed to port fuel injection (PFI) where fuel is mixed with air before entering the combustion chamber. GDI provides more precise control over fuel injection timing and atomization, resulting in higher combustion efficiency and lower fuel consumption[6].

- Advantages: GDI engines can achieve higher specific power output and better fuel economy due to more efficient air-fuel mixing and combustion. The precise fuel injection timing allows for leaner air-fuel ratios, reducing fuel consumption and CO_2 emissions.
- Challenges: Despite these advantages, GDI engines are prone to higher levels of particulate emissions due to incomplete combustion, especially under low-load conditions. Advanced after-treatment systems, such as gasoline particulate filters (GPFs), are often required to mitigate this issue.

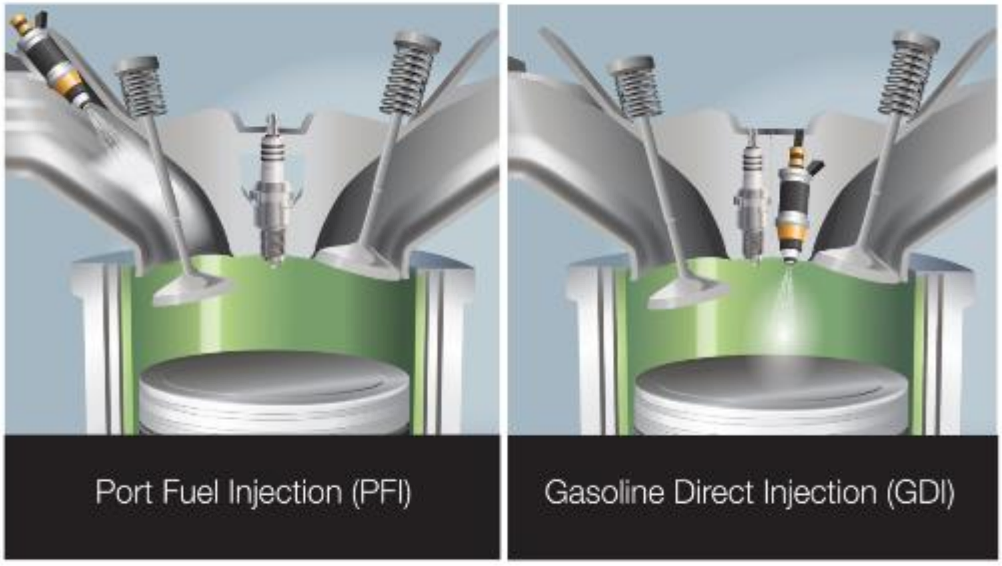

Figure 5 Comparison of GDI and PFI combustion systems

3.4 Low-Temperature Combustion (LTC)

Low-Temperature Combustion (LTC) is a strategy that aims to minimize combustion temperatures to reduce NOx and soot formation. By maintaining lower in-cylinder temperatures, LTC can reduce the chemical reactions responsible for NOx production while also minimizing soot emissions.

- Key Technologies:
  - Exhaust Gas Recirculation (EGR): Reintroducing a portion of the exhaust gases into the combustion chamber reduces the oxygen content and lowers the combustion temperature.
  - Advanced Fuel Injection Strategies: LTC often requires sophisticated fuel injection techniques to ensure adequate fuel-air mixing at lower temperatures, preventing the formation of soot while maintaining combustion stability.
- Advantages: LTC provides a significant reduction in both NOx and soot emissions. Additionally, it enables efficient combustion at low temperatures, which can contribute to improved thermal efficiency in certain operating conditions.
- Challenges: LTC can suffer from ignition delay and combustion instability, particularly at low engine loads. Controlling combustion under varying speeds and loads while maintaining low temperatures is a critical challenge.

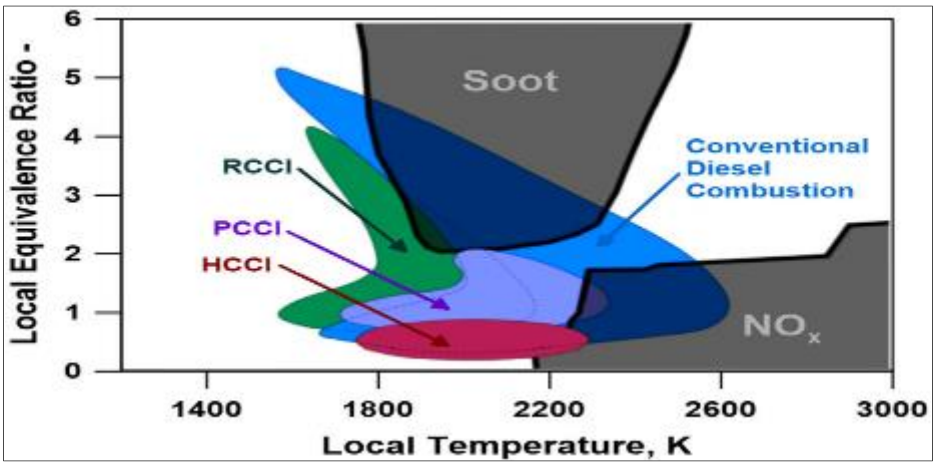

Figure 6 In-cylinder pressure and temperature map

4 Technological Enablers

The effectiveness of advanced combustion strategies such as HCCI, RCCI, GDI, and LTC heavily depends on the supporting technologies that enhance combustion control, efficiency, and emissions reduction. This section discusses the key technological enablers that contribute to the successful implementation of these advanced combustion methods [7].

4.1 Variable Valve Timing (VVT)

Variable Valve Timing (VVT) technology adjusts the timing of the opening and closing of engine intake and exhaust valves. By optimizing the valve timing according to engine load, speed, and operating conditions, VVT enhances air-fuel mixture formation, improves combustion efficiency, and reduces emissions. VVT is particularly beneficial for achieving optimal operation in strategies such as HCCI and LTC, where precise control over the intake and exhaust gases is crucial.

- Benefits for Advanced Combustion:
    - In HCCI, VVT helps control the internal residual gases, which play a key role in managing combustion temperature and enabling auto-ignition.
    - In LTC, VVT helps maintain low combustion temperatures by managing the exhaust gases and ensuring proper fuel-air mixing at reduced temperatures.
- Challenges: Implementing VVT in engines requires sophisticated electronic control systems to adjust valve timing in real time. Additionally, the interaction between VVT and other engine systems, such as turbocharging and fuel injection, must be carefully coordinated for optimal performance.

4.2 Turbocharging and Supercharging

Turbocharging and supercharging are technologies that increase the pressure of the intake air, allowing more air to enter the combustion chamber. This increase in air pressure leads to higher engine power output, improved thermal efficiency, and lower CO_2 emissions. Turbocharging, in particular, is widely used in conjunction with advanced combustion strategies to enhance engine performance while meeting stringent emission regulations.

- Turbocharging: Utilizes the engine's exhaust gases to drive a turbine, which compresses the intake air. This process significantly improves the efficiency of CI and GDI engines, where higher air-fuel ratios lead to cleaner and more efficient combustion.

- Supercharging: Uses a mechanical compressor, often driven by the engine's crankshaft, to compress the intake air. Supercharging provides immediate boosts in power, especially at lower engine speeds, making it useful in high-performance applications.

- Advantages for Combustion Strategies:
    - In GDI systems, turbocharging allows for better fuel atomization and higher air-fuel mixing efficiency, leading to improved combustion and reduced emissions.
    - Turbocharging and supercharging are also compatible with LTC strategies, where higher air pressure helps maintain combustion stability at lower temperatures.

4.3 Advanced Ignition Systems

The development of advanced ignition systems has opened up new possibilities for improving combustion stability and efficiency. Traditional spark ignition systems are limited in their ability to ignite lean or highly diluted air-fuel mixtures. To overcome these limitations, advanced ignition technologies such as laser ignition, plasma ignition, and corona discharge ignition have been developed.

- Laser Ignition: Uses focused laser beams to initiate combustion. This system allows for more precise ignition timing and location, enabling the ignition of ultra-lean air-fuel mixtures, which reduces fuel consumption and emissions.

- Plasma Ignition: Generates high-energy plasma to ignite the fuel mixture. Plasma ignition is more effective than traditional spark ignition in initiating combustion in dilute mixtures, which can improve efficiency and reduce emissions.

- Corona Discharge Ignition: Utilizes an electrical corona to create a larger ignition zone, allowing for faster and more reliable combustion across a wide range of engine loads and speeds.

- Benefits for Combustion:
  - Advanced ignition systems allow for leaner combustion, which leads to lower CO_2 and NOx emissions.
  - They enable better control over ignition timing, helping optimize combustion in GDI and HCCI engines where precise ignition control is crucial.

5 Hybrid Combustion Strategies

Combining advanced combustion strategies with hybrid-electric powertrains can significantly enhance overall efficiency and reduce emissions[8].

- Electric-Assisted Combustion: The integration of electric motors allows for optimized engine load conditions, facilitating more efficient combustion. By providing additional torque during acceleration or assisting in maintaining optimal operating conditions, electric motors can reduce reliance on the internal combustion engine (ICE), leading to lower fuel consumption and emissions.

- Hydrogen Combustion: Utilizing hydrogen as a supplemental fuel in dual-fuel configurations presents an opportunity for achieving near-zero carbon emissions. Advanced combustion control techniques, such as precise timing systems, enable better management of hydrogen combustion characteristics, enhancing performance while minimizing pollutants. This approach not only leverages existing infrastructure but also paves the way for future sustainable energy sources.

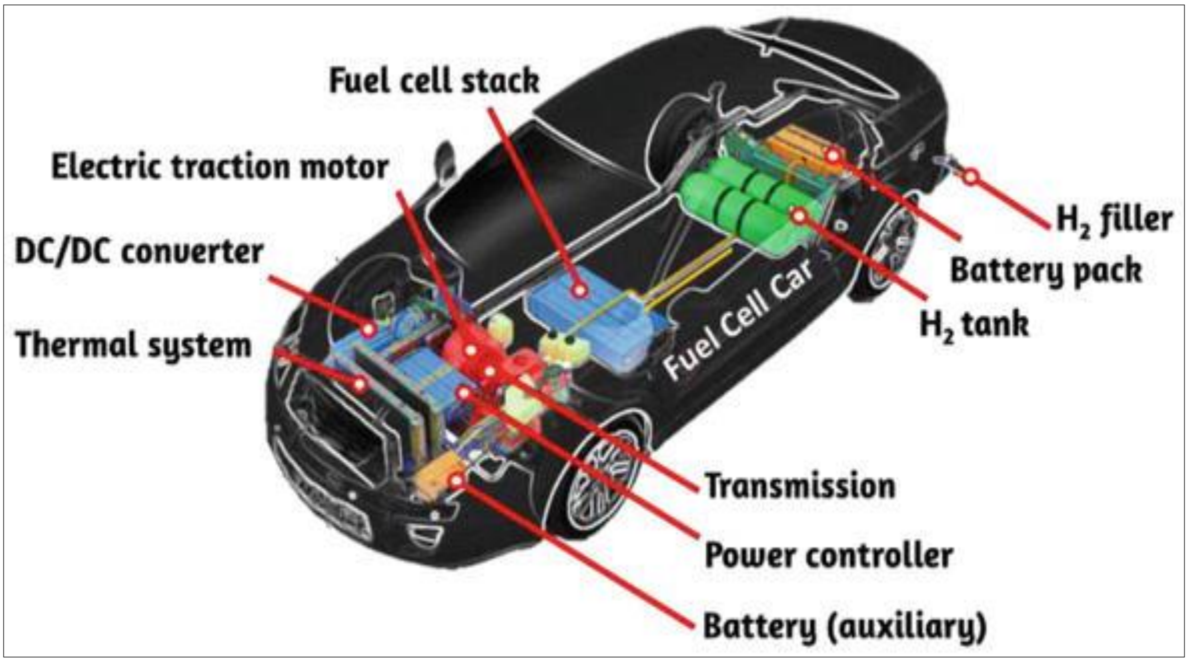

Figure 7 Hybrid combustion system integrating electric motors and hydrogen fuel**.**

6 Emission Control Technologies

Emission control systems are vital for minimizing pollutants from advanced combustion engines, with key technologies including three-way catalytic converters, selective catalytic reduction (SCR), and diesel particulate filters (DPF)[9].

- Three-Way Catalysts: Employed in spark-ignition (SI) engines, these catalysts effectively control carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons (HC) emissions. They function optimally under stoichiometric conditions, promoting simultaneous reduction of these harmful emissions.

- SCR and DPF Systems: Selective catalytic reduction (SCR) and diesel particulate filters (DPF) are primarily utilized in compression-ignition (CI) engines. SCR systems reduce NOx emissions by injecting a reductant, such as urea, into the exhaust stream, while DPFs capture particulate matter (PM) to minimize soot emissions. Together, these technologies enhance compliance with stringent emission regulations.

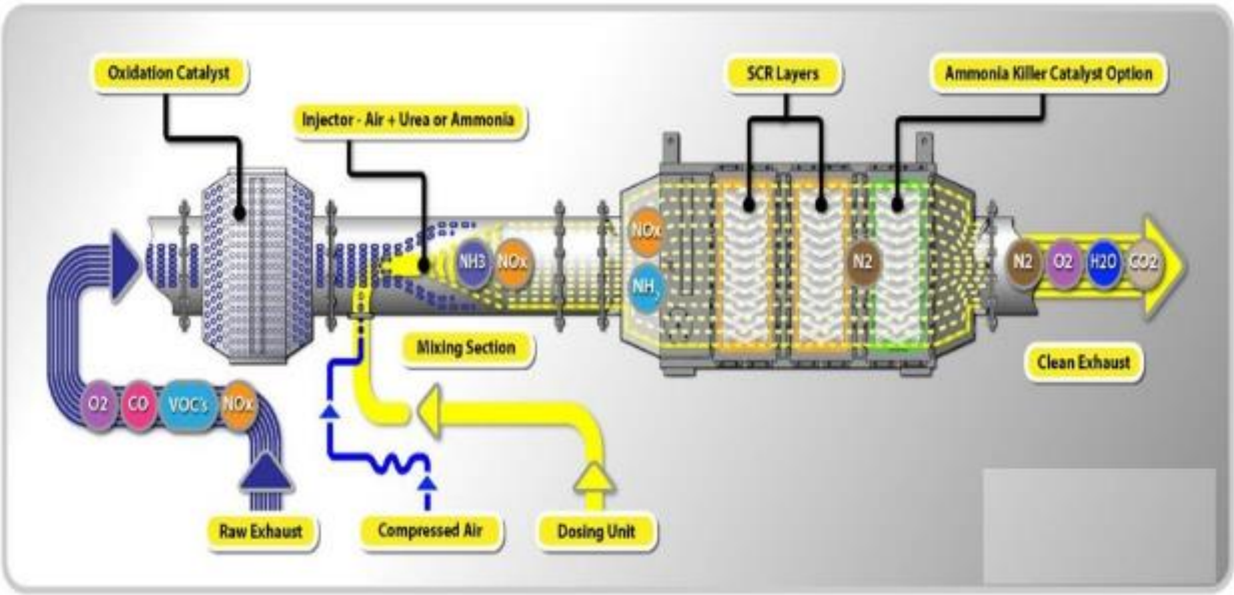

Figure 8 Schematic of a modern exhaust after-treatment system

7 Simulation and Optimization Techniques

The development of advanced combustion strategies necessitates sophisticated simulation tools for effective design and optimization. Techniques such as computational fluid dynamics (CFD) and machine learning (ML) play crucial roles in enhancing engine performance and efficiency.

- Computational Fluid Dynamics (CFD): CFD simulations are integral for analyzing fluid flow, heat transfer, and combustion processes within the engine. By creating detailed models of the combustion chamber, engineers can study the interactions between fuel and air, optimize spray characteristics, and analyze the effects of turbulence and temperature distribution. These insights allow for the optimization of Homogeneous Charge Compression Ignition (HCCI) combustion, which operates at leaner fuel-air mixtures and significantly minimizes emissions. Additionally, CFD aids in understanding combustion stability and identifying conditions that lead to knock or misfire, enabling more reliable engine operation.
- Machine Learning (ML): Machine learning techniques can process and analyze vast datasets generated from engine tests and simulations, identifying complex patterns and correlations that traditional modeling methods may overlook. By training algorithms on historical performance data, ML can optimize combustion parameters, enhance fuel injection strategies, and predict engine performance under various operating conditions. For instance, ML can be employed to fine-tune control strategies in real-time, adapting to changing conditions and improving overall efficiency. Moreover, ML models can facilitate predictive maintenance by forecasting potential issues based on usage patterns, further enhancing the reliability of advanced combustion systems.
- Integration of CFD and ML: The combination of CFD and ML represents a powerful approach to engine optimization. CFD can generate high-fidelity data that serves as training input for ML models, enabling them to learn from complex fluid dynamics and combustion processes. This integration can lead to more accurate predictions and optimizations, ultimately resulting in cleaner and more efficient engine designs.

8 Challenges and Future Trends

Despite their numerous advantages, advanced combustion strategies encounter several significant challenges that need to be addressed for wider adoption and implementation[9,10]:

- Control Complexity: Achieving precise control over combustion phasing, fuel injection timing, and mixture preparation is critical for optimizing engine performance. Advanced combustion modes, such as HCCI and PCCI (Premixed Charge Compression Ignition), require sophisticated control systems to manage varying combustion characteristics effectively. This complexity can lead to increased development costs and necessitates highly skilled personnel for tuning and maintenance.

- Operating Range Limitations: Many advanced combustion strategies, particularly HCCI, face limitations in their operational range. The difficulty in controlling auto-ignition across different engine speeds and loads can restrict the effective range of these strategies. Operating at extremes may result in incomplete combustion, increased emissions, or engine knock, thereby compromising efficiency and reliability.

- Material and Cost Considerations: The implementation of advanced combustion technologies often requires new materials capable of withstanding higher pressures and temperatures. This can lead to increased production costs and complexity in manufacturing. Moreover, the need for durable components that can endure the aggressive environments created by these combustion processes poses additional engineering challenges.

The future of advanced combustion strategies is likely to be shaped by several key trends:

- Integration of Renewable Fuels: The transition to renewable fuels such as hydrogen, synthetic fuels, and biofuels is expected to play a pivotal role in the evolution of combustion technologies. These fuels can enhance sustainability and significantly reduce carbon emissions, aligning with global environmental goals. Research into efficient dual-fuel systems and blending strategies will further facilitate this transition.

- Advanced Control Algorithms: The application of artificial intelligence (AI) and machine learning (ML) in engine control systems is set to revolutionize advanced combustion strategies. AI-driven algorithms can optimize combustion in real-time, adapting to varying operating conditions and enhancing overall efficiency. By continuously learning from operational data, these systems can improve predictive maintenance and minimize emissions.

- Hybridization and Electrification: The ongoing trend toward hybrid and fully electric powertrains will also influence the development of advanced combustion strategies. Combining these technologies can lead to more efficient energy management, reducing reliance on fossil fuels while still leveraging the benefits of advanced combustion in certain applications.

9 Conclusion

Advanced combustion strategies have the potential to significantly enhance the efficiency of internal combustion (IC) engines while reducing emissions. Technologies such as Homogeneous Charge Compression Ignition (HCCI), Reactivity Controlled Compression Ignition (RCCI), Gasoline Direct Injection (GDI), and Low-Temperature Combustion (LTC) are leading this evolution, especially when integrated with innovations like turbocharging and hybrid powertrains. These approaches allow for improved control over the combustion process, enabling leaner operation and increased thermal efficiency.To fully realize the benefits of these advanced strategies, continued research is essential in several areas, including combustion optimization, material advancements, and emission control technologies. Developing new materials to withstand higher pressures and temperatures, alongside innovative emission control systems, will be crucial for meeting stringent environmental regulations. By focusing on these areas, the automotive industry can create cleaner, more efficient engines that align with sustainability goals.

Reference

[1] Singh, Akhilendra Pratap, and Avinash Kumar Agarwal. "Characteristics of particulates emitted by ic engines using advanced combustion strategies." Advanced engine diagnostics (2019): 57-71.

[2] Dahham, Rami Y., Haiqiao Wei, and Jiaying Pan. "Improving thermal efficiency of internal combustion engines: recent progress and remaining challenges." Energies 15, no. 17 (2022): 6222.

[3] Singh, Akhilendra Pratap, and Avinash Kumar Agarwal. "Low-temperature combustion: an advanced technology for internal combustion engines." Advances in internal combustion engine research (2018): 9-41.

[4] Liang, Xingyu, Yuesen Wang, Yu Chen, and Sili Deng. "Advances in emission regulations and emission control technologies for internal combustion engines." SAE International Journal of Sustainable Transportation, Energy, Environment, & Policy 2, no. 13-02-02-0007 (2021): 101-119.

[5] Manente, Vittorio, Claes-Goeran Zander, Bengt Johansson, Per Tunestal, and William Cannella. An advanced internal combustion engine concept for low emissions and high efficiency from idle to max load using gasoline partially premixed combustion. No. 2010-01-2198. SAE Technical Paper, 2010.

[6] Doppalapudi, Arun Teja, A. K. Azad, and M. M. K. Khan. "Combustion chamber modifications to improve diesel engine performance and reduce emissions: A review." Renewable and Sustainable Energy Reviews 152 (2021): 111683.

[7] Joshi, Ameya. "Review of vehicle engine efficiency and emissions." SAE International Journal of Advances and Current Practices in Mobility 1, no. 2019-01-0314 (2019): 734-761.

[8] Reitz, Rolf D., H. Ogawa, R. Payri, T. Fansler, S. Kokjohn, Y. Moriyoshi, A. K. Agarwal et al. "IJER editorial: The future of the internal combustion engine." International Journal of Engine Research 21, no. 1 (2020): 3-10.

[9] Payri, F., José M. Luján, Carlos Guardiola, and B. Pla. "A challenging future for the IC engine: new technologies and the control role." Oil & Gas Science and Technology–Revue d'IFP Energies nouvelles 70, no. 1 (2015): 15-30.

[10] Baweja, Sarthak, and Rajan Kumar. "Efficiency Improvement of Internal Combustion Engines Over Time." Novel Internal Combustion Engine Technologies for Performance Improvement and Emission Reduction (2021): 147-173.