Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/31/20240962

Advancements in homogeneous charge compression ignition technology: Efficiency, emissions, and applications in the modern automotive industry

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Abstract. Homogeneous charge compression ignition (HCCI) technology is a novel approach in internal combustion engines that combines the efficiency of gasoline engines with the spontaneous ignition characteristics of diesel engines. HCCI engines offer cleaner emissions, reduced noise, and wider fuel adaptability, overcoming many drawbacks of traditional engines. The paper explores the HCCI combustion process, highlighting its unique features and advantages over spark ignition (SI) and compression ignition (CI) engines. It also discusses innovations in HCCI technology, including its combination with other strategies like spark-controlled compression ignition (SCCI) and low-temperature combustion (LTC) to expand its load range. The challenges of HCCI technology, especially in combustion timing control, are addressed, along with suggestions for future research directions. The application of HCCI technology for energy savings and emission reduction and its impact on the automotive industry are also discussed, citing examples from manufacturers like Volvo, Nissan, and General Motors. The paper concludes by emphasizing the importance of ongoing research, integration with other technologies, and financial support to further advance HCCI technology and its market potential.

Keywords: Homogeneous charge compression ignition (HCCI) technology, Energy Saving, Emission Reduction

1. Introduction

HCCI fuel is a novel fuel generated by blending gasoline and diesel. The combustion process of this fuel is similar to that of gasoline engines but adopts the combustion characteristics of diesel, hence HCCI is also referred to as “the gasoline engine with diesel’s spontaneous ignition characteristics [1]. Through recent years of research, it has been found that HCCI engines can operate under “ultra-delayed low-temperature mixed gas auto-ignition” conditions, achieving efficient and clean combustion processes that overcome some disadvantages of conventional gasoline and diesel engines. HCCI engines exhibit lower noise, cleaner emissions, wider fuel adaptability, and reduced emissions of nitrogen oxides and particulates [2]. Recognized as a significant technological breakthrough in the field of internal combustion engines, HCCI technology overcomes the drawbacks of traditional gasoline and diesel engines. However, controlling the combustion process of HCCI engines is challenging, and their working load range is narrow, necessitating further research. Overall, HCCI engines have broad application prospects and market potential. Research on HCCI fuel mainly aims to improve engine

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thermal efficiency, reduce fuel consumption, lower emissions, enhance environmental friendliness, expand the engine load range, and implement mixed fuel applications [3].

To date, there have been many significant contributions: achieving low-temperature ultra-delayed auto-ignition of the mixed gas, improving thermal efficiency, substantially reducing emissions compared to traditional gasoline engines, utilizing mixed gasoline and diesel, expanding fuel adaptability, accumulating data for the development of after-treatment technology, and laying the foundation for hybrid power and electronic control internal combustion engine technology. This article aims to delve deeply into HCCI technology and its applications and prospects in the modern automotive industry.

2. Overview of HCCI Engine

The HCCI combustion process is a unique mechanism. At the end of the engine's compression stroke, it utilizes the heat generated by compression to achieve auto-ignition of the homogeneous premixed fuel-air mixture, replacing the traditional spark plug ignition process [4]. During this process, fuel and air are quickly and thoroughly premixed in the intake manifold, forming a mixture. As the piston rises, the mixture is compressed but does not produce a flame, instead increasing in pressure and temperature continuously. When temperature and pressure reach a certain value, the mixture auto-ignites and completes combustion in a very short time, then enters the expansion stroke, where the high-temperature and high-pressure gas expands, driving the piston.

There are several significant differences between the HCCI combustion process and traditional gasoline engine combustion. Firstly, their ignition methods are different: HCCI relies on auto-ignition of the mixture at the end of the compression stroke, while gasoline engines depend on sparks produced by spark plugs. Secondly, HCCI has a faster combustion rate, completing the majority of mixture combustion within a few crankshaft degrees, whereas the flame in gasoline engines needs more time to spread from the igniter. Moreover, HCCI has a lower peak temperature, typically within the 1800-2000K range, closer to isothermal combustion, while gasoline engines can exceed 2500K. This results in HCCI having higher thermal efficiency, improving by over 15%, whereas traditional gasoline engines have relatively lower thermal efficiency. In terms of emissions, HCCI produces fewer nitrogen oxides and particulates. However, it also brings challenges, especially in controlling the combustion timing, which is more difficult than in traditional gasoline engines that can directly control ignition timing.

The initial temperature and pressure of the mixture play a crucial role in the HCCI combustion process. A higher initial temperature makes the mixture more likely to reach the auto-ignition temperature, leading to earlier combustion. Correspondingly, a larger initial pressure can lower the mixture's ignition temperature, also causing earlier combustion. At the same time, air-fuel ratio and mixture composition are important factors affecting HCCI combustion. When the air-fuel ratio is close to the stoichiometric ratio, auto-ignition of the mixture is most likely to occur. It's worth noting that the residual gas components in the mixture also affect its auto-ignition properties, hence requiring control and adjustment during the mixing process. Furthermore, fuel type and injection strategy also play important roles in HCCI combustion. Different volatilities of fuels require different mixing strategies to meet the needs of HCCI combustion. In actual operation, the choice of injection timing and whether to adopt multiple injection strategies will directly affect the generation process of the mixture and the final auto-ignition timing. Comprehensive consideration and precise control of these factors are key to achieving efficient HCCI combustion [5].

3. Innovations in HCCI Technology

3.1. Comparison of HCCI Technology with Other Engine Technologies

In HCCI technology, the fuel and air are mixed very uniformly, and combustion is achieved when the conditions for auto-ignition are met through compression. This mode of combustion is more efficient, reducing both fuel consumption and emissions [6]. Spark Ignition (SI) is a mode of combustion where air and fuel are mixed and then ignited by an electric spark generated by a spark plug, suitable for gasoline engines. Compression Ignition (CI) is primarily for diesel engines, where fuel is directly

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injected into compressed air, and auto-ignition is achieved through the high temperature generated by compressed air.

In terms of efficiency, HCCI has a higher thermal efficiency due to the more uniform mixing of fuel and air, allowing for more complete combustion. This can increase thermal efficiency by more than 15%, bringing it closer to the ideal isothermal combustion process [7]. The SI has a lower thermal efficiency because the rate of combustion affects its performance significantly, preventing it from fully utilizing the energy from the fuel. While CI's mixture is not as uniform even though it also relies on compression combustion, its thermal efficiency is still slightly lower than HCCI.

Regarding emission performance, HCCI significantly reduces NO_x and PM emissions. Due to its fuller and more uniform combustion, harmful emissions can be reduced by over 60%. SI engines produce more NO_x emissions because they operate at higher combustion temperatures, leading to increased nitrogen oxide formation. CI engines, due to the uneven mixture of fuel and air, produce more PM and NO_x emissions.

From the above comparisons, it's evident that the HCCI mode of combustion has significant advantages in efficiency and emission performance compared to the traditional SI and CI modes. This is because HCCI achieves more uniform and complete combustion, reducing fuel consumption and harmful emissions and making it more environmentally friendly and economical.

Moreover, HCCI technology can also be combined with other engine technologies. For instance, there have been significant research advancements in the combined strategy and optimization of HCCI with Spark-Controlled Compression Ignition (SCCI). Studies show that through mixture gas preparation and employing strategies like SCCI, Premixed Charge Compression Ignition (PCCI), and Low-Temperature Combustion (LTC), the high load limit of HCCI engines can be effectively increased [8]. By combining SCCI combustion, the operational range of HCCI can be extended to higher loads. Additionally, by optimizing the properties of the HCCI and SCCI mixture gas in terms of temperature and mixture preparation strategy, the efficiency and performance of HCCI combustion can be further enhanced [9]. Experimental and multi-zone chemical kinetics model research has also indicated that using two-stage ignition fuels for partial fuel stratification can effectively smooth the heat release rate of HCCI, thus enhancing the high-load performance of the engine. Finally, the combination of HCCI, SCCI, and Low-Temperature Combustion (LTC) also demonstrates superior thermal efficiency and ultra-low NOx and soot emissions, providing strong support for achieving more efficient and low-emission engine performance. These research achievements provide valuable references and guidance for the combined strategy and optimization of HCCI and SCCI, contributing to the realization of more efficient and eco-friendly engine technologies.

3.2. HCCI Combustion Timing Control Technology

The technology to control the HCCI combustion timing is a core challenge to push its commercialization. This is because timing control directly determines the engine's combustion conditions and operational stability. Inaccurate timing control can lead to a series of problems, including misfires, intense oscillations, and abnormal combustion. These not only impact the engine's performance and lifespan but also increase maintenance costs. Current HCCI timing control technology has made some progress. Techniques such as exhaust gas recirculation (EGR), varying the compression ratio, and implementing two-stage supercharging can indirectly perform thermal control, thus indirectly affecting the combustion timing. Additionally, direct fuel injection technology and the addition of ignition promoters are used to alter the auto-ignition properties of the mixture, offering more possibilities for timing control. Existing control systems also employ fuzzy control and neural network techniques to achieve efficient control over HCCI combustion timing. However, there's still room for improvement in current technology, and future research should focus on developing more accurate real-time combustion models and model predictive control techniques for more precise timing control. Fast and sensitive sensor technology will also be a focal point of future research. These sensors can monitor combustion parameters in real-time, providing real-time feedback to the control system. Additionally, more robust control algorithms need to be developed to enhance the real-time nature and stability of the control system. Ultimately, advanced techniques, like laser technology, could be explored for direct control of auto-ignition timing, which is expected to further enhance the accuracy and reliability of HCCI timing control. These integrated techniques and methods will collectively advance the commercialization process of HCCI combustion technology.

4. Application of HCCI Technology in Energy Saving and Emission Reduction

The HCCI engine, with its unique mode of combustion, possesses significant potential for energy saving and emission reduction. Specifically, its efficient combustion process can improve thermal efficiency by over 15%, meaning that under the same conditions, the fuel consumption of HCCI engines can be reduced by 15%. According to rough estimates, if all vehicles in the country adopted HCCI technology, about 5 million tons of gasoline could be saved annually. For individual vehicles, the fuel consumption of domestic passenger cars can be reduced by 8%-15%. In contrast, the fuel consumption reduction for commercial vehicles might exceed 10%, thus resulting in a total cost reduction of over 7% for long-distance transportation. Furthermore, the HCCI engine performs excellently in reducing nitrogen oxide (NO_x) emissions, with emission levels being reduced by over 60%. If this technology were widely applied, it is estimated that approximately 3 million tons of NO_x emissions could be reduced annually. This would not only aid in improving urban atmospheric conditions and reducing the probability of smog occurrences but would also significantly decrease greenhouse gas emissions, thereby yielding substantial environmental protection benefits. Regarding the mechanism of NO_x reduction, HCCI significantly reduces NO_x formation through low-temperature combustion (with peak temperatures ranging between 1600-1800K). This low-temperature combustion process lowers the rate of nitrogen decomposition, shortens high-temperature residence time, decreases the volume of high-temperature areas, and collectively reduces the opportunities for nitrogen oxide formation.

In addition, the combination of HCCI engines and renewable fuels presents new opportunities for environmental protection. The use of renewable fuels not only reduces dependence on petroleum but also aids in improving the overall combustion efficiency of the fuel. However, this also introduces challenges due to the uneven quality of renewable fuels and their varied auto-ignition characteristics, which demand higher requirements for mixed gas preparation and combustion control in HCCI systems. To overcome these challenges, researchers need to intensify studies on the combustion process of renewable fuels, develop advanced adaptive control systems, and optimize HCCI system parameters to accommodate different types of renewable fuels [10]. This includes adaptability research and evaluation of various renewable fuels, such as alcohol fuels (like methanol, ethanol, etc.) converted from biomass, biodiesel, bio-aviation fuels, and non-hydrocarbon fuels like syngas. Through these efforts, HCCI technology is expected to integrate better with renewable fuels, achieving higher energy-saving and emission-reduction effects.

Current technology is unavailable to effectively control combustion phasing as it is influenced by fuel concentration, mixture homogeneity, compression ratio, and other engine-dependent parameters. There are several challenges, including problems with initiating combustion under high load conditions, limitations in power output, and difficulties associated with homogeneous mixture preparation for fuels with reduced volatility like Diesel. These challenges necessitate further research and development efforts.

5. Application and Prospects of HCCI Technology in Modern Automotive Industry

5.1. Current Practical Application

Volvo Cars, Nissan, and General Motors have all incorporated HCCI technology into their engine series to enhance combustion efficiency and reduce harmful emissions. Specifically, General Motors successfully integrated mechanical and electronic control of HCCI technology in some of their V-type engines. This technology optimizes engine performance by combining traditional mechanical control with advanced Electronic Control Units (ECUs) to ensure precise combustion control and dynamic parameter adjustment. The ECU can monitor and adjust various performance parameters of the engine

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in real-time, such as combustion efficiency, fuel consumption, and emission levels, maintaining optimal engine performance under different working environments and driving demands. This integrated technology allows the engine to sustain efficient combustion and stable power output across a broad working range and significantly reduces NO_x and particulate emissions through precise ECU control. Although controlling HCCI technology is complex, General Motors successfully addressed these challenges, ensuring stable and reliable operation of HCCI technology in V-type engines through advanced sensor technology, control algorithms, and continuous optimization experiments. This innovative initiative has not only advanced General Motors' technology but also provided valuable technical support and practical experience for the energy-saving and emission-reduction goals of the automotive industry.

5.2. Impact of HCCI Technology on the Automotive Industry

HCCI technology has profoundly impacted the automotive industry, marking a significant leap in engine technology and the industry as a whole. Firstly, it significantly reduces fuel consumption by dramatically improving engine thermal efficiency. The increase in engine thermal efficiency means that fuel energy can be more effectively converted into power, thus reducing fuel consumption while maintaining or increasing power output, creating tangible economic benefits for consumers. Secondly, HCCI technology has made a significant contribution to reducing harmful gas emissions. By optimizing the combustion process, this technology not only reduces the emissions of toxic gases like nitrogen oxides and carbon monoxide but also significantly lowers particulate emissions, providing strong support for improving environmental quality and addressing climate change issues. Moreover, HCCI technology also enhances the vehicle's power and economy while extending the engine's maintenance cycle. Through a more complete and efficient combustion process, it not only enhances engine power output and response speed but also reduces internal engine wear and deposits, thereby extending the maintenance cycle and engine life, saving maintenance and care costs for car owners. Finally, the introduction of HCCI technology has spurred rapid development and innovation in engine technology, laying a solid foundation for the transformation and upgrading of the entire automotive industry. With increasingly stringent environmental standards and growing consumer demand for efficient, low-emission vehicles, the application of HCCI technology offers automotive manufacturers a viable technical route, helping them better adapt to market changes, meet environmental protection requirements, and maintain and improve competitiveness in intense market competition. In summary, HCCI technology has made significant contributions to promoting the green and sustainable development of the automotive industry.

5.3. Suggestions for Future Research and Development Directions

To ensure the continuous development and maturation of HCCI technology, several research and development directions should be deeply explored. These include further optimization of HCCI control strategies, expansion of the range of fuels suitable for HCCI technology, strengthening of simulation and rapid control algorithm development, and integration with other advanced automotive and engine technologies. Additionally, there should be increased investment and support from relevant enterprises and research institutions to ensure the effective promotion and application of HCCI technology. Through a coordinated research and development strategy, HCCI technology is expected to achieve greater technological breakthroughs and market success in the future.

To ensure the continuous and maturing development of HCCI technology in the future, there are several research and development directions worth paying attention to and deeply exploring. Firstly, future research needs to continue optimizing HCCI control strategies, especially addressing the auto-ignition problems in the high-load region. Auto-ignition in high-load regions represents a significant technical challenge in HCCI technology, necessitating sophisticated control strategies and system designs to ensure stable and efficient combustion under various operating conditions. Secondly, expanding the range of fuels suitable for HCCI technology is another important research direction. Current HCCI technology is primarily designed and optimized for specific fuel types, and future

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research should explore and validate the adaptability and performance of HCCI technology with various fuels, including traditional fuels and alternative energy fuels, to achieve broader applications and higher energy efficiency. Furthermore, strengthening the development of simulation technologies and rapid control algorithms is crucial for advancing HCCI technology. Through the use of high-precision simulation technologies and algorithms, researchers can more accurately understand and predict the dynamic characteristics and performance of the HCCI combustion process, providing important theoretical foundations and technical support for the design and optimization of control strategies. Additionally, future HCCI technology development should focus on integration and compatibility with other advanced automotive and engine technologies. Through organic integration with other technologies, HCCI can achieve better system performance and optimization, maximizing its technical advantages and market potential. Lastly, to ensure the effective promotion and application of HCCI technology, related enterprises and research institutions need to increase investment and support. With adequate funding and resource support, the R&D process of HCCI technology can be accelerated, facilitating its transition from the laboratory to the market and realizing its widespread industrial and commercial application. In summary, through comprehensive and coordinated research and development strategies, HCCI technology is expected to achieve greater technological breakthroughs and market success in the future.

6. Conclusion

HCCI technology plays a crucial role in enhancing engine performance and environmental friendliness. Firstly, in terms of combustion control and stability, achieving stable HCCI combustion control is a core technical challenge. Recent research has significantly improved the stability and controllability of HCCI engines by optimizing combustion control strategies, refining fuel injection systems, and finely adjusting the premixing level of in-cylinder mixed gas. Secondly, regarding emission control, while HCCI technology significantly reduces emissions of nitrogen oxides (NOx) and particulate matter (PM), it is important to note that it may lead to an increase in carbon monoxide (CO) and hydrocarbon (HC) emissions. Researchers have successfully mitigated these side effects and further optimized the environmental performance of HCCI engines by developing and applying a series of emission control strategies, including external exhaust gas recirculation (EGR) and selective catalytic reduction (SCR). Furthermore, in terms of fuel flexibility, HCCI engines demonstrate significant adaptability to various types of fuels, such as gasoline, diesel, natural gas, and various biomass fuels, showcasing broad development potential across various applications, including light vehicles, heavy trucks, and generators. In terms of control strategies and intelligence, researchers can further improve the performance and efficiency of HCCI engines through the adoption of advanced control strategies and intelligent technologies, such as deep learning and artificial neural networks. These advanced technologies allow for real-time monitoring of engine operating conditions and adjustment of combustion parameters as needed to maximize engine performance optimization. Finally, on the practical application front, HCCI technology has achieved demonstrative success in multiple fields, especially in light and heavy vehicles. Some leading global automotive manufacturers have launched mass-produced models equipped with HCCI engines, with the main advantages being significantly improved fuel economy and reduced harmful emission levels, meeting the stringent requirements of the market and environmental regulations.

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