The Development and Future Trends in HCCI and DF-PCCI Engines for Sustainable Transportation

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Abstract. Internal combustion (IC) engines have long been the dominant technology in transportation, but their environmental impact, particularly in terms of air pollution, has become a growing concern. To address these challenges, advanced combustion technologies like homogeneous-charge compression ignition (HCCI) and dual-fuel premixed-charge compression ignition (DF-PCCI) engines have been developed. This paper explores the potential of HCCI and DF-PCCI engines to serve as more sustainable alternatives to conventional IC engines by analysing their combustion mechanisms, thermal efficiency, and emissions performance. While both engines offer significant environmental benefits, such as lower NO_x, particulate matter, and CO_2 emissions, they each face unique challenges in terms of fuel injection control, biofuel integration, and combustion stability. DF-PCCI demonstrates advantages in combustion phasing and high-load performance, while HCCI requires further development in fuel injection and exhaust gas recirculation (EGR) systems. Hybridization emerges as a promising solution to improve the flexibility and real-time control of both engines. Ultimately, this paper highlights the potential of HCCI and DF-PCCI engines to significantly reduce transportation-related emissions and contribute to global sustainability goals.

Keywords: Homogeneous-charge compression ignition (HCCI); exhaust gas recirculation (EGR); internal combustion (IC).

1. Introduction

In modern society, IC engines play a crucial role in transportation. Observing the public's daily travel choices, it is evident that the use of IC engines has remained prevalent in recent years. To enhance the efficiency of IC engines and address global concerns about air pollution, particularly those raised by the United Nations, various new types of IC engines have been developed. Air pollution, primarily resulting from fuel combustion, is responsible for approximately one in nine deaths worldwide [1]. In light of this, the importance of developing sustainable transportation has become increasingly pressing. Engines must become cleaner and more efficient to meet these environmental challenges. The development of HCCI engines and DF-PCCI engines represents a significant step in this direction. Both technologies offer cleaner exhaust emissions and greater efficiency compared to conventional gasoline engines. This paper aims to explore the feasibility of HCCI and DF-PCCI engines becoming pioneers of sustainable engines in everyday life.

2. Background of HCCI Engines

The combustion mechanism of HCCI engines significantly differs from that of traditional IC engines. Unlike conventional engines, HCCI engines do not utilize spark plugs; instead, they rely on compressing a homogeneously distributed flammable gas mixture within the cylinder until it reaches the autoignition temperature, triggering combustion [2]. Given this mechanism, the fuel-gas mixture is rapidly compressed in the cylinder. To mitigate the resulting pressure increase, a leaner fuel mixture is typically used [3].

One of the notable characteristics of HCCI engines is their lower emissions of NO_x and particulate matter (PM). This is attributed to the fact that HCCI engines operate under relatively low-temperature conditions during combustion, which prevents the formation of pronounced flames and reduces the likelihood of smoke formation, even when using specialized fuels. Another important advantage of

HCCI engines is their thermal efficiency. For instance, increasing the hydrogen content in the fuel from 0% to 20% has been shown to raise the energy efficiency of HCCI engines from 45.26% to 55.45%, while the exergy efficiency improved from 41.15% to 46.14% [4].

The trend in engine design is increasingly shifting toward the adoption of HCCI technology, while spark ignition is gradually being phased out. However, HCCI engines have not yet fully replaced spark ignition and conventional compression ignition engines due to several manufacturing challenges. One of the key obstacles is the control of the combustion phase. The method of fuel injection in HCCI engines is critical, as improper fuel-wall interaction can negatively affect HC emissions, carbon monoxide (CO) emissions, particulate matter (PM) production, brake specific fuel consumption (BSFC), and oil dilution [5]. Achieving optimal control of the HCCI combustion phase requires adjusting the fuel's tendency toward spontaneous ignition or modifying the time-temperature profile to which the fuel blend is subjected. However, a feasible method for controlling combustion phasing has not yet been identified in manufacturing.

In recent advancements, Mazda has successfully incorporated HCCI technology into its production vehicles. The "Skyactiv-X" engine is the first commercial gasoline engine to utilize HCCI technology. This innovation allows the engine to operate at an air-fuel ratio of over 30:1, compared to the conventional 14.7:1 ratio, resulting in reduced fuel consumption. Nonetheless, despite this progress, there remains significant room for improvement in HCCI engine development.

3. Role of DF-PCCI in Advancing Engine Technology

Dual fuel-premixed charge compression ignition (DF-PCCI) represents an advanced and innovative combustion technology. In DF-PCCI, a large portion of the diesel mixture combusts during the premixed combustion phase, which leads to a reduction in NOx and particulate matter (PM) emissions [6]. DF-PCCI operates at relatively low combustion temperatures compared to other combustion technologies. This process involves premixing the fuel and induction charge, followed by compression-induced combustion once the fuel reaches the necessary ignition temperature [6].

When comparing HCCI and DF-PCCI technologies, DF-PCCI offers more straightforward control over combustion phasing. By optimizing the natural gas substitution ratio and diesel injection timing, both the combustion phase and burn duration can be effectively regulated, eliminating the need for exhaust gas recirculation [7]. DF-PCCI provides significant advantages, particularly under high load conditions. Numerous studies have shown that DF-PCCI can operate effectively at load levels comparable to conventional diesel combustion (CDC) [8-10]. Furthermore, DF-PCCI demonstrates a substantial potential for reducing CO_2 emissions. In a specific study, incorporating a 40% natural gas substitution rate resulted in a 14.5% decrease in CO_2 emissions from DF-PCCI combustion compared to CDC. This reduction is primarily attributed to DF-PCCI's ability to efficiently utilize low-carbon fuels like natural gas [7].

4. The Efficiency Improvements in HCCI and DF-PCCI Engines

Despite the high thermal efficiency and combustion stability of HCCI and DF-PCCI engines, there are still several measures that can further enhance their performance. For HCCI engines, substantial potential for improvement remains, particularly in the use of biofuels. Due to their high oxygen content, biofuels can promote the oxidation of carbon monoxide in the hot cylinder, thereby reducing toxic emissions. Additionally, incorporating a low-temperature combustion strategy in HCCI engines can decrease the production of nitrogen oxides. However, the use of biofuels in HCCI engines presents challenges, such as increased ICP and heat release rate (HRR), caused by premature combustion and difficulties in temperature control. Future developments will need to address these issues, possibly through modifications in the fuel injection strategy [11].

In addition to biofuels, other strategies can further improve engine efficiency. For example, the integration of more sophisticated, learning-capable machines could optimize engine performance.

Machine learning models can enhance the accuracy of performance forecasts by analysing important operational parameters, thereby maximizing fuel efficiency in engines [12]. More precise machines can also facilitate better supervisory control, allowing real-time management and adjustment of machine parameters to optimize engine operation. HCCI engines require advanced control systems, which rely heavily on electronic control systems. Therefore, the development of more refined electronic control systems is crucial for monitoring real-time data and adjusting specific engine parameters as needed. Given the numerous factors that influence HCCI engine performance, improved electronic control systems can provide deeper insights into how to enhance engine efficiency [13].

From an economic perspective, using learning models to optimize biofuel production processes can reduce the costs associated with fuel manufacturing, making biofuels more competitive with traditional gasoline and diesel fuels [12]. Comparing to the HCCI engines, DF-PCCI engine have more advantages than HCCI engine (Figure 1).

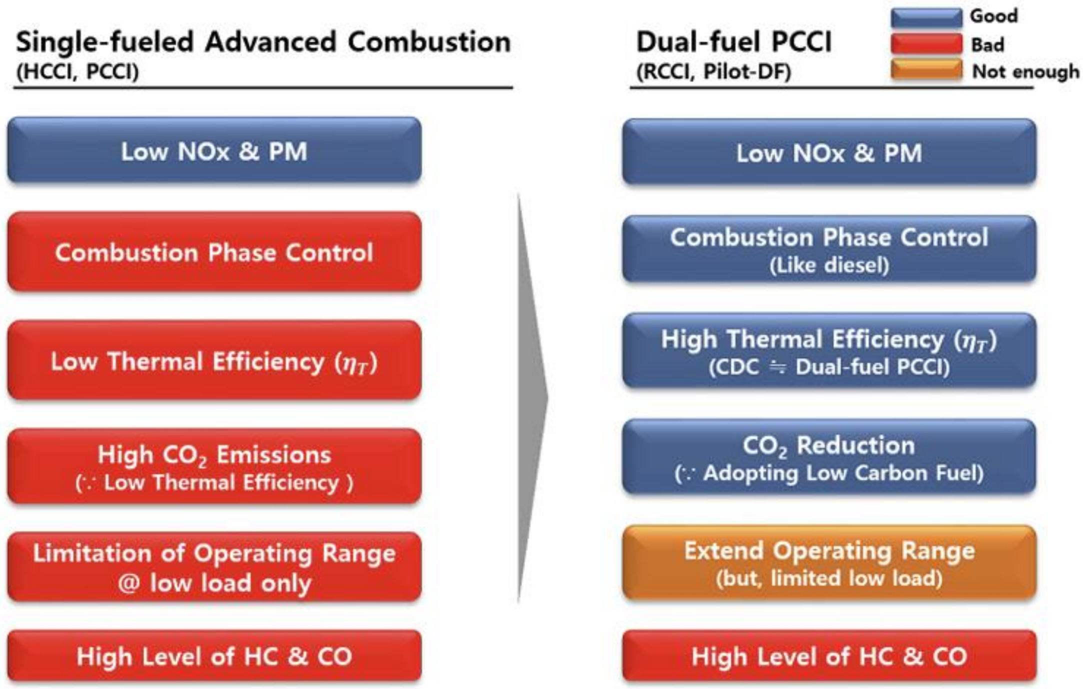

Fig 1. Comparison of HCCI and RCCI engine [12].

In this study, it is evident that the DF-PCCI engine outperforms the HCCI engine in several key areas, including higher thermal efficiency, enhanced thermal stability, a relatively broader operating range, and a significant reduction in carbon dioxide emissions. However, to make DF-PCCI a practical technology for the future, further research is needed, particularly in reducing total hydrocarbon emissions under low load conditions [7].

5. Current challenges in HCCI and DF-PCCI engine development

Although HCCI engines exhibit high thermal efficiency and low exhaust gas emissions, several challenges must be addressed before this technology can be practically implemented. Issues such as fuel introduction, the fuel-to-air mixture ratio, and the control of ignition timing all contribute to operational difficulties in HCCI engines. These challenges can result in improper engine operation, reduced combustion efficiency, and increased emissions of unburned hydrocarbons. To facilitate the commercial application of HCCI technology, a more flexible fuel injection system is required, one that can ensure thorough mixing of the fuel before ignition. Additionally, advancements in controlled combustion and EGR systems are necessary to significantly reduce exhaust emissions. Implementing these improvements will enhance the performance of HCCI engines, accelerating their market introduction and contributing to the reduction of NO_x and particulate matter emissions [14].

One of the limitations of HCCI engines is the significant increase in hydrocarbon emissions. To make HCCI engines more adaptable and versatile, they must be designed to perform efficiently under a wide range of environmental conditions [15]. Future development of HCCI engines will focus on investigating the performance, combustion, and emission characteristics when using biofuels. The adoption of biofuels not only ensures improved performance but also offers excellent exhaust emissions control.

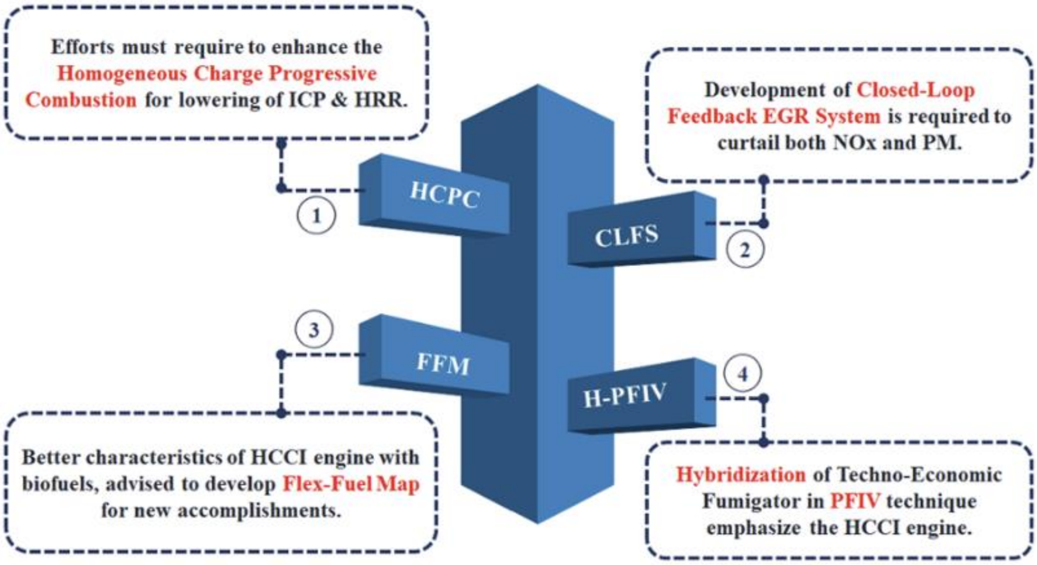

Fig 2. Future development goals of the HCCI engine [15].

The development of HCCI and DF-PCCI engines presents promising advancements in combustion technology, with each engine offering significant environmental and efficiency benefits. HCCI engines, in particular, face challenges related to early injection strategies, which can lead to rapid combustion, resulting in high ICP and heat release rates (HRR). These issues increase the risk of knocking and wear on engine components. To mitigate this, HCPC is a promising solution that requires further research, particularly in the context of biofuels, which could enhance combustion control and reduce emissions. However, the use of biofuels in HCCI engines presents its own set of challenges, such as managing in-cylinder pressure and heat release rates, necessitating improvements in fuel injection strategies to ensure smoother engine operation (Figure 2).

HCCI engines also benefit from the use of EGR to achieve ultralow NOx emissions through low-temperature combustion. However, the inherent trade-off between NO_x and PM emissions limits the use of EGR, and future developments in this area will be critical for improving overall engine performance. Additionally, flex-fuel maps offer a significant opportunity for performance enhancement in HCCI engines, but substantial research is still needed to fully optimize their application. Another area of focus is the external homogeneous charge preparation technology, which currently requires large carburettors and high power to vaporize viscous fuels. Developing hybrid port fuel injection vaporization (PFIV) systems is a necessary step to improve the efficiency and practicality of HCCI engines.

The introduction of hybrid technology into HCCI and DF-PCCI engines further expands their potential. Hybridization allows for greater flexibility in engine control, particularly under low-load conditions, and research suggests that integrating hybrids with HCCI engines is both feasible and beneficial. This development could lead to a significant reduction in emissions and improved fuel efficiency. The synergy between hybrid systems and these advanced combustion engines offers a promising path for future engine technologies [16].

From a sustainability perspective, the market introduction of HCCI and DF-PCCI engines could greatly reduce CO_2 emissions and improve fuel economy. These advancements would contribute to global efforts to mitigate climate change and address environmental pollution. Given that conventional internal combustion engines were responsible for 80% of greenhouse gas emissions from fuel cycles in 2010 and 2014, the shift to HCCI and DF-PCCI engines could result in a substantial reduction in global emissions, aligning with the United Nations' sustainable development goals. This technological progress holds the potential to significantly reduce the environmental impact of transportation and foster more sustainable global development.

6. Conclusion

In conclusion, the development and potential market introduction of HCCI and DF-PCCI engines represent significant advancements in the pursuit of sustainable and efficient combustion technologies. Both engines offer considerable environmental benefits, including reduced emissions of nitrogen oxides (NOx), particulate matter (PM), and carbon dioxide (CO_2), as well as higher thermal efficiency compared to traditional internal combustion engines. However, several challenges remain, particularly in the optimization of combustion control, fuel injection strategies, and the integration of biofuels. Addressing these challenges will be critical for the commercial viability of HCCI and DF-PCCI engines.

The HCCI engine, while offering low emissions and high efficiency, faces obstacles related to its combustion phase control, particularly when utilizing biofuels. Enhancing fuel injection systems, EGR, and electronic control systems will be crucial to unlocking the full potential of this technology. DF-PCCI engines, on the other hand, show more immediate promise due to their greater ease of combustion phase control and ability to operate under high load conditions. Nonetheless, further research is needed to reduce hydrocarbon emissions and optimize their performance under low load conditions. Hybridization presents a valuable opportunity to enhance the flexibility and performance of both HCCI and DF-PCCI engines, particularly in terms of real-time control and fuel efficiency. Integrating these engines with hybrid systems could further reduce emissions and enhance their environmental impact, contributing to the global effort to mitigate climate change. Ultimately, the continued development and refinement of HCCI and DF-PCCI engines will be vital to achieving global sustainable development goals. These technologies have the potential to significantly reduce the environmental footprint of transportation and play a crucial role in shaping the future of cleaner, more efficient engines. By addressing the current challenges and continuing to explore innovative solutions, HCCI and DF-PCCI engines could become key contributors to a more sustainable and environmentally conscious transportation sector.

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