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

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Abstract:

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

Introduction:

Internal combustion engines play a crucial role in transportation and power generation, contributing significantly to global energy consumption and emissions. To address environmental concerns and enhance efficiency, researchers have been exploring alternative combustion strategies, leading to the development of HCCI, PCCI, and RCCI technologies. This study focuses on the utilization of alcohol fuels, such as ethanol and methanol, in these combustion modes.

Homogeneous Charge Compression Ignition (HCCI):

Homogeneous Charge Compression Ignition (HCCI) is a type of internal combustion in which well-mixed fuel and oxidizer (usually air) are compressed to the point of auto-ignition. As with other types of combustion, this exothermic reaction generates heat that can be converted into work in a heat engine.

HCCI combines the features of conventional gasoline and diesel engines. Gasoline engines use a combination of homogeneous charge (HC) and spark ignition (SI), abbreviated HCSI. Modern direct injection diesel engines combine stratified charge (SC) and compression ignition (CI), known as SCCI.

As with HCSI, HCCI injects fuel during the intake stroke. Instead of using an electric discharge (spark) to ignite a portion of the mixture, HCCI compresses the mixture to increase density and temperature until it reacts spontaneously.

Stratified charge compression ignition also relies on the temperature and density increase caused by compression. However, it injects fuel later in the compression stroke. Combustion occurs at the fuel-air interface, producing higher emissions while allowing for a leaner and higher compression burn, resulting in greater efficiency.

Controlling HCCI necessitates microprocessor control and a thorough understanding of the ignition process. HCCI designs produce emissions comparable to those of a gasoline engine while maintaining the efficiency of a diesel engine.

HCCI engines emit extremely low levels of NOx without a catalytic converter. To comply with automobile emission control regulations, hydrocarbons (unburned fuels and oils) and carbon monoxide emissions must still be treated [1].

Premixed charge compression ignition (PCCI):

PCCI evolved from the HCCI combustion model to improve control over the start of combustion. It can address issues in the HCCI model, such as combustion noise and uncontrolled combustion phases. It achieves the desired ignition delay by using enhanced charge motion that is not fully homogeneous, a lower compression ratio, higher injection pressure, and extensive exhaust gas recirculation (EGR). In the PCCI combustion model, fuel can be injected into the combustion chamber in three different ways: advanced direct, port fuel, and late direct injection. Advanced direct injection and port fuel injection emit HC and CO due to fuel impingement on the cylinder wall. However, narrow spray angle injectors and EGR reduce wall impingement which is avoided by late direct injection and provides a means of switching the combustion style to conventional combustion at higher loads. A newer approach in PCCI involves air-fuel premixing via early injection, followed by a late injection of fuel pulse during the compression stroke, which controls the onset of ignition. Higher EGR causes a longer ignition delay, allowing for better air-fuel mixture and fewer fuel-rich pockets in LTC. It can reduce both NOx emissions and soot levels in PCCI [2].

Reactivity Controlled Compression Ignition (RCCI):

RCCI combustion compresses well-mixed low-reactivity fuel and oxidizer (typically air) without causing auto-ignition. Later, during the compression cycle, high-reactivity fuel is injected to create a local mixture of low and high reactivity fuel. Finally, high-reactivity fuel is injected near the piston's top dead center, igniting the entire fuel charge. The RCCI combustion process requires two distinct fuels. Low-reactivity fuel is injected into the intake ports under low pressure during the intake stroke. When the compression stroke is complete, high-reactivity fuel is injected into the cylinder under high pressure. A throttle similar to Otto engines is not required. Because of compression ignition and a lack of throttle control, RCCI closely resembles the diesel process. The dual-fuel RCCI can emit ultra-low NOx and soot emissions and high thermal efficiency compared to conventional diesel combustion [3].

Comparison between HCCI, PCCI, RCCI Engine Technologies:

1. Combustion Characteristics: HCCI uses a homogeneous mixture of fuel and air to ignite spontaneously due to high temperature and pressure. This combustion mode presents difficulties in regulating ignition timing and achieving stable combustion, particularly with alcohol fuels. While HCCI has lower peak temperatures, which reduces NOx formation, the lack of direct ignition control makes it difficult to optimize performance across a range of operational conditions.

PCCI combines elements of both spark and compression ignition, giving you more control over the combustion process. This produces a more controlled burn than HCCI, making it appropriate for a wider range of operating conditions.
RCCI controls combustion phasing by using two fuels with different reactivity, typically diesel and gasoline. This dual-fuel approach seeks to strike a balance between efficiency and emission control [4].

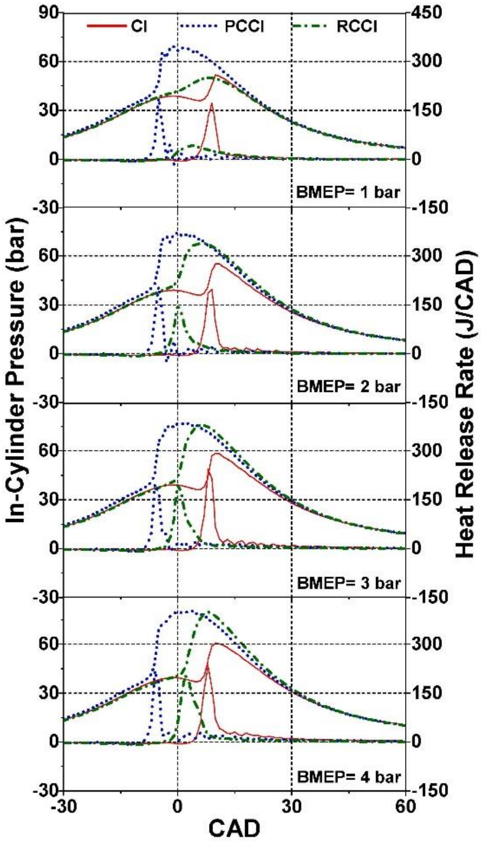

Fig. 1. In-cylinder pressure and heat release rate variations for baseline CI, PCCI and RCCI combustion modes at varying engine loads.

2. Fuel Properties: HCCI is versatile and can be used with various fuels, including alcohol. Its reliance on auto-ignition makes it compatible with alcohol fuels such as ethanol, promoting fuel diversification and reducing reliance on conventional fossil fuels.

PCCI has a wide range of fuel options, but it prefers fuels with good auto-ignition properties. Alcohol fuels, with their advantageous properties, can improve the performance of PCCI engines.
RCCI necessitates careful selection of dual fuels with varying reactivities. While alcohol fuels may not be appropriate for both components of the dual-fuel system, they can help to achieve the desired reactivity characteristics.

3. Ignition Control: Controlling ignition timing precisely is a major challenge for HCCI systems. The auto-ignition process limits the ability to adjust ignition in response to changing engine loads and speeds, reducing overall efficiency.

By combining compression ignition and controlled spark ignition, PCCI allows for more precise ignition timing control. This dual-control approach improves the engine's adaptability to different loads and speeds.

RCCI allows for precise control over combustion phasing by adjusting the proportions of the two fuels. This precise control enables the optimization of performance and emissions under a variety of operating conditions.

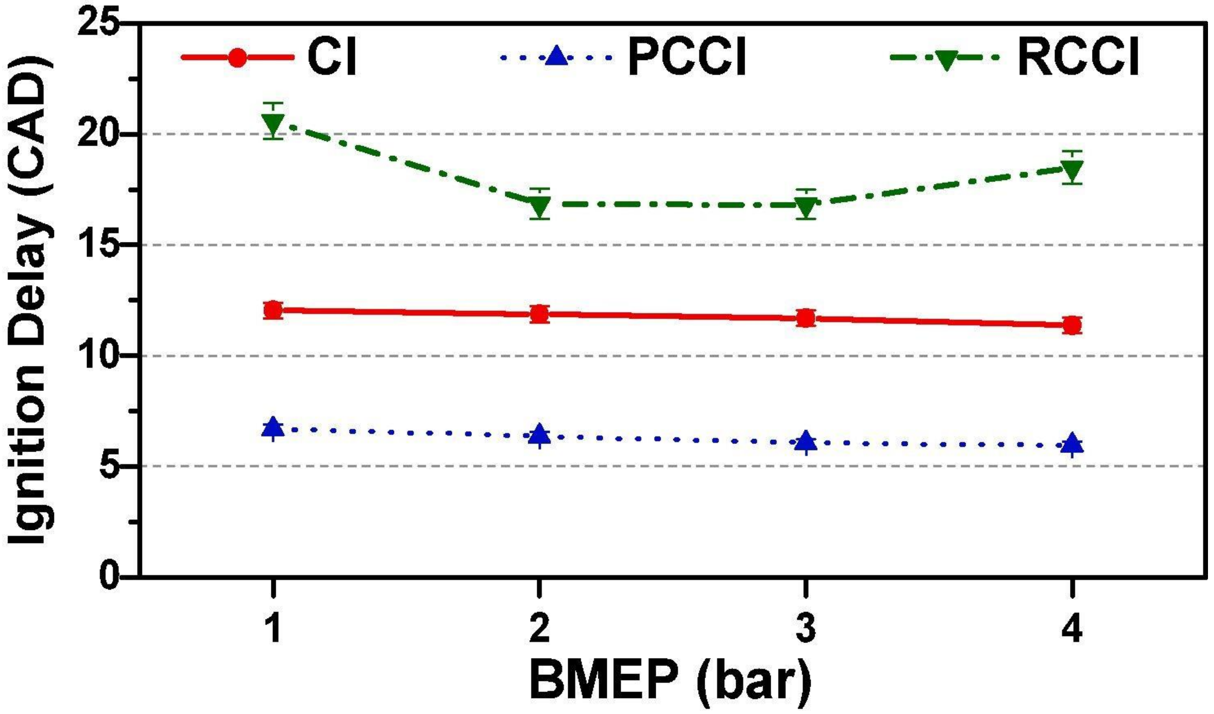

Fig. 2. Ignition delay of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

4. Emissions: Despite lower NOx emissions, HCCI still faces challenges in controlling unburned hydrocarbons and carbon monoxide. Optimizing the combustion process to address these issues is critical for meeting stringent emissions regulations.

PCCI outperforms HCCI in terms of emission control, with lower NOx and better combustion stability. This makes PCCI a promising technology for meeting strict emissions regulations.

RCCI combines the benefits of compression ignition with reduced NOx emissions and improved fuel efficiency. The dual-fuel strategy allows for fine-tuning of combustion parameters, resulting in reduced environmental impact [5].

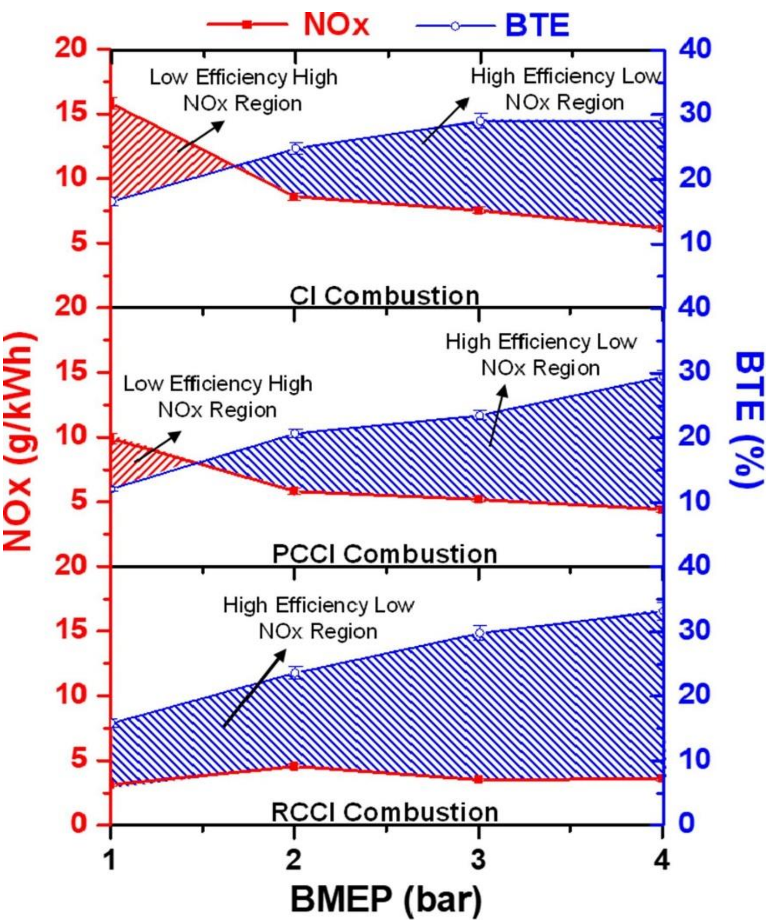

Fig. 3. NOx-BTE trade-off of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

5. Efficiency: HCCI can achieve high thermal efficiency by reducing heat losses through a leaner combustion process. However, achieving and maintaining this efficiency over a wide range of operating conditions remains a major research priority.

PCCI engines are more efficient than conventional spark-ignition engines. Controlled combustion improves the utilization of fuel energy, contributing to increased overall efficiency.

RCCI technology combines the efficiency advantages of compression ignition with the combustion control normally associated with spark ignition. This synergy helps to improve overall engine efficiency [6].

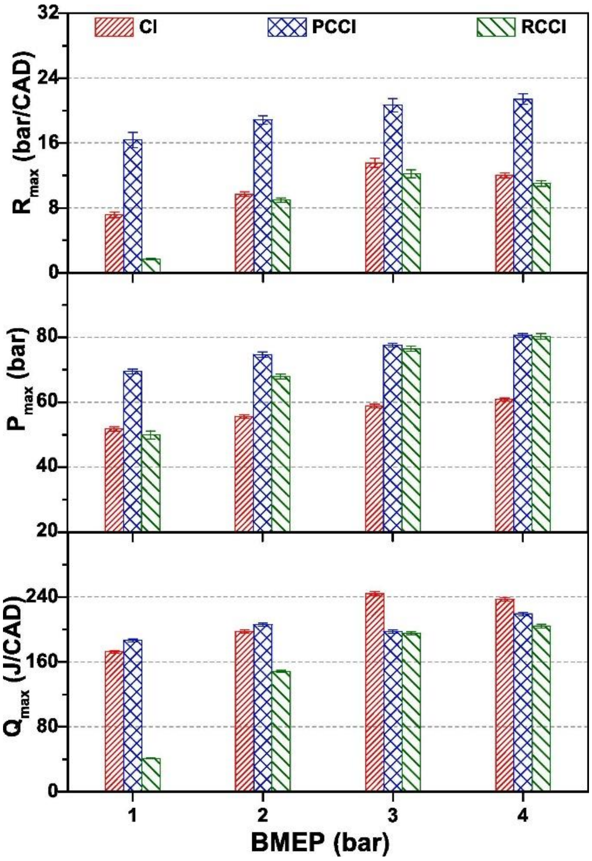

Fig. 4. R_{max}, P_{max}, and Q_{max} of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

6. Cold Start and Load Range: HCCI's reliance on auto-ignition limits its load range and poses challenges during cold starts. These limitations limit its usefulness in certain driving situations and climates.

PCCI engines have better cold start characteristics and a wider load range than HCCI engines, making them more adaptable to a variety of driving conditions.

RCCI engines have good load flexibility, which alleviates some of the cold-start issues associated with HCCI. The dual-fuel capability provides the versatility required for a variety of driving conditions.

Conclusion:

The comparative study highlights the differences between HCCI, PCCI, and RCCI engine technologies when fuelled with alcohol. While HCCI provides fuel versatility and the potential for high thermal efficiency, it faces ignition control issues. PCCI's combined ignition strategies provide better control over combustion and emissions. RCCI, which uses dual fuels, strikes a balance between compression ignition benefits and lower NOx emissions, demonstrating superior adaptability under a variety of driving conditions. The selection of these technologies is determined by specific requirements, emphasizing the importance of ongoing research and development to refine and optimize advanced combustion technologies for a sustainable and efficient future in transportation.

Reference:

1. *"College of Engineering @ The University of Wisconsin-Madison, initiatives in energy, health, nanotechnology, security, and information technology". Engr.wisc.edu. Archived from the original on 2010-02-25. Retrieved 2014-03-31.*

2. Boot M, Rijk E, Luijten C, Somers B, Albrecht B. Spray impingement in the early direct injection premixed charge compression ignition regime, SAE Technical Paper - 2010-01-1501: 2010

3. *Paykani, Amin; Kakaee, Amir-Hasan; Rahnama, Pourya; Reitz, Rolf D (2016-06-01). "Progress and recent trends in reactivity-controlled compression ignition engines". International Journal of Engine Research. **17** (5): 481–524. doi:10.1177/1468087415593013. ISSN 1468-0874.*

4. J.B. Heywood

Internal combustion engine fundamentals
McGraw-Hill Book Company, New York (1988)

5. Automotive Vehicles − Exhaust Emissions − Gaseous Pollutants from Vehicles Fitted with Compression Ignition Engines − Method of Measurement; Indian Standard IS 14273; Bureau of Indian Standards, New Delhi, India, 1999.

Google Scholar

6. A.P. Singh, N. Sharma, V. Kumar, A.K. Agarwal

Experimental investigations of mineral diesel/ methanol-fueled reactivity controlled compression ignition engine operated at variable engine loads and premixed ratios
Int J Engine Res (2020), 10.1177/1468087420923451
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