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A Review on Hydrogen Integration in low temperature Combustion Engines

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Abstract:

This compilation of research papers delves into strategies for mitigating exhaust emissions in internal combustion engines by utilizing low-CO2 fuels, with a particular focus on LTC-Reactivity Controlled Dual Fuel Engines (RCCI). One study explores the intricacies of RCCI engines employing a blend of hydrogen-enhanced natural gas and diesel, emphasizing the impact of diesel injection timing on engine performance under varying loads. Another investigation examines the use of oxy-hydrogen gas as a fuel additive in a PCCI engine, showcasing its efficacy in reducing carbon monoxide (CO) and hydrocarbon (HC) emissions during PCCI mode. The study of hydrogen addition on combustion characteristics in an HCCI engine reveals that dilution effects outweigh chemical effects in influencing combustion variations. Additionally, a separate inquiry aims to enhance hydrogen's role in compression ignition engines through the testing of low-temperature combustion strategies, including retarded injection timing and water injection.

Furthermore, a numerical analysis scrutinizes the effects of hydrogen on biogas combustion in an HCCI engine, uncovering changes in nitrogen oxide (NO) emissions, carbon dioxide (CO2) levels, and lean operation limits. Lastly, an RCCI engine fueled with a combination of compressed natural gas (CNG) and biodiesel demonstrates reduced emissions and heightened efficiency, particularly in CNG/biodiesel mode, showcasing stable combustion with decreased carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions. Together, these studies collectively underscore promising avenues for emissions reduction and efficiency improvement through the strategic integration of hydrogen and other low-CO2 fuels in internal combustion engines.

***Keywords**: Reactivity Controlled compression Engine (RCCI), Hydrogen, HCCI engines (Homogeneous Charge Compression Ignition) PCCI- Premixed Charge Compression Ignition*

Introduction:

In this set of research papers, the main focus is on finding effective ways to cut down on exhaust gas emissions by using low-CO2 fuels. The spotlight is on Reactivity Controlled Dual Fuel Engines (RCCI), which show promise in significantly reducing emissions. One specific study takes a closer look at injection strategies that impact RCCI combustion engines, especially when using hydrogen-enriched natural gas as a low-reactive fuel. Another key area of research explores a wide range of low-carbon fuels such as ammonia, hydrogen, methane, and renewable alcohols, aiming to contribute to broader efforts in decarburization. The papers also delve into optimizing combustion in diesel engines by strategically incorporating hydrogen, exploring injection and reactivity strategies to improve both performance and emission reduction.

Additionally, there are efforts to enhance the role of hydrogen in RCCI engines by using a blend of diesel oil and natural gas enriched with hydrogen or syn-gas. The research also examines the use of oxy-hydrogen gas as a fuel additive in Premixed Charge Compression Ignition (PCCI) engines to reduce NOx and soot emissions. Various studies explore hydrogen combustion in noble gases, investigating optimal parameters for combustion and predicting ignitability. Numerical analyses are conducted to scrutinize the effects of hydrogen addition on natural gas/dimethyl-ether RCCI engines and HCCI engines, covering combustion characteristics, emissions, and performance. Overall, these papers highlight the significance of dual-fuel compression ignition engines, with hydrogen emerging as a promising candidate for future energy systems. The research also explores the potential of biodiesel and natural gas as alternatives to diesel fuel, investigating low-temperature combustion strategies to reduce emissions and enhance fuel efficiency in internal combustion engines.

Mirosław et al,2021, addresses the challenge of reducing exhaust gas emissions by exploring the potential of using fuels with hydrogen as an additive or through hydro-treatment. It underscores the effectiveness of reactivity-controlled dual fuel engines (RCCI) as a promising approach for utilizing these fuels in internal combustion engines. The focus is on how low-temperature combustion in RCCI engines enables the use of modern, highly efficient fuels, leading to a further reduction in CO2 emissions.

The paper not only compiles existing research on this topic but also draws conclusions about the feasibility of promoting the use of these fuels across various applications and their potential for widespread adoption. In essence, it offers a comprehensive review of low-CO2 emission fuels tailored for dual-fuel RCCI engines, emphasizing their capacity to mitigate exhaust emissions and meet the growing restrictions on emissions.

Akshay et al,2023, addresses Hydrogen (H2) and natural gas (NG) are becoming increasingly appealing as fuels for internal combustion engines due to concerns surrounding fossil fuel depletion and the need to address harmful emissions. One promising strategy for achieving emission reduction and enhancing engine efficiency is the dual-fuel combustion approach, particularly reactivity-controlled compression ignition (RCCI).

In this study, the focus is on examining the in-cylinder combustion behavior of RCCI engines that use hydrogen-added natural gas as a low-reactive fuel, combined with diesel as a highly reactive fuel. The investigation employs numerical simulations conducted on a 2.44 L heavy-duty engine, exploring three load conditions and six stages by adjusting the diesel injection timing.

The introduction of hydrogen to natural gas led to a notable decrease in harmful emissions such as carbon monoxide (CO) and unburnt hydrocarbon, with only a slight increase in NOx generation. During low load conditions, the optimal performance, as indicated by the maximum imep (indicated mean effective pressure), was achieved with an advanced injection timing of -21OATDC (after top dead center). However, as the load increased, the optimum timing shifted to a retarded position.

The findings underscore the significant role played by diesel injection timing in determining the engine's performance under varying load conditions. Overall, this research sheds light on the potential of using hydrogen and natural gas in RCCI engines to effectively reduce emissions while optimizing engine performance.

Leilei et al, 2023, explores the feasibility of utilizing ammonia as the primary fuel in heavy-duty engines as part of efforts to reduce carbon emissions. The focus is on a Reactivity Controlled Compression Ignition (RCCI) engine, where a small amount of diesel is used to ignite a mixture of ammonia and air.

To validate their findings, the researchers used a numerical model and combustion mechanism, comparing them with experimental results from engines using methanol and iso-octane fuels. They also measured the ignition delay times of ammonia/n-heptane mixtures in a rapid compression machine.

The results indicate that the engine can effectively operate with up to 50% of the total energy supplied by premixed ammonia. However, this comes with a slight increase in NO emissions compared to a traditional diesel-fueled engine. Further increasing the ammonia content leads to a decrease in combustion efficiency.

The study also explores the possibility of using hydrogen to enhance ammonia combustion in the engine. While this approach does improve ammonia combustion, it also results in a further increase in NO emissions.

Amitav et al,2021,delves into the effective use of hydrogen as a less reactive component to enhance the transition regimes of partially premixed and reactivity-controlled combustion in a diesel engine. The study employs Response Surface Methodology (RSM) to pinpoint the optimal interposed zone of operation.

The results reveal that increasing the rate of hydrogen induction enhances the stability of the interposed combustion zone. Through optimization, the researchers achieved an impressive 31.58% exergy efficiency and 99.1% desirability. This optimized regime led to significant reductions in soot (45.09%), total unburnt hydrocarbon (TUHC) (14.29%), and NOx emissions (39.83%) compared to a similar trial run.

Importantly, the research showcases that variable injection and reactivity phasing, coupled with hydrogen enrichment, can bring about advanced low-temperature combustion (LTC) concepts in an existing diesel engine without necessitating major design modifications.

Mehran et al,2022, utilizes a modified single-cylinder heavy-duty diesel engine, incorporating features such as a bathtub piston bowl profile and a compression ratio of 14.88:1. The engine operates within its mid-load range, ranging from 9.4 to 13.5 bar gross IMEPs.

To address the challenge of NOx emissions associated with using pure hydrogen, the study employs Exhaust Gas Recirculation (EGR) and nitrogen addition as air-hydrogen diluents. Advanced Start of Injection (SOI) timing is also implemented.

Simulation results indicate that in a hydrogen-fueled RCCI engine, the diesel fuel energy share can be reduced to approximately 13%, while the Hydrogen Energy Share (HES) percentage can be increased up to 87%. The engine load loss is minimal, at less than 6%, with a Gross Indicated Efficiency (GIE) exceeding 48%, all without encountering diesel knock.

Furthermore, the study demonstrates that the hydrogen-fueled RCCI engine can meet the EURO VI standards for Carbon Monoxide (CO) and Unburned Hydrocarbon (UHC) emissions, as well as the EPA standards for Formaldehyde emissions. Notably, achieving the EURO VI standard for NOx emissions, a notable challenge for hydrogen-fueled engines, is also attainable.

Hadi et al 2020,aims to boost the share of hydrogen energy in a Reactivity Controlled Compression Ignition (RCCI) engine using a blend of natural gas and diesel oil. This is achieved by introducing hydrogen or syngas mixed with exhaust gas recirculation.

The study reveals that the addition of hydrogen to natural gas allows for an increase in the hydrogen energy share within the engine, reaching up to 40.43% with only a minimal reduction in engine power output. Similarly, introducing syngas to natural gas enhances the hydrogen energy share to 27.05% while improving engine power by over 4%.

Two different strategies are explored for introducing hydrogen or syngas into the engine, both resulting in a significant reduction in hydrocarbon fuel consumption per cycle—up to 46.60% and 33.86%, respectively.

The RCCI engine, fueled with a combination of natural gas, diesel oil, and hydrogen or syngas, achieves a gross indicated efficiency exceeding 50%. Additionally, there is a notable reduction in engine emissions compared to RCCI combustion fueled solely with natural gas and diesel oil.

Nikhil et al,2021,explores the effectiveness of using oxy-hydrogen gas as a fuel additive in a Premixed Charge Compression Ignition (PCCI) engine with the aim of reducing carbon monoxide (CO) and hydrocarbon (HC) emissions. The engine underwent a conversion from a conventional diesel combustion (CDC) engine to a PCCI engine, achieved through port fuel injection of diesel fuel and preheating of air.

The introduction of oxy-hydrogen gas resulted in notable improvements in indicated mean effective pressure and indicated thermal efficiency, attributed to accelerated chemical reactions. The study found an average reduction in CO emissions of 26.19% at 25% load and 18.88% at 50% load, and an average reduction in HC emissions of 19.27% at 25% load and 23.74% at 50% load. Importantly, NOx emissions remained within the range of 10 parts per million (ppm) even with the addition of oxy-hydrogen gas.

Furthermore, the inclusion of oxy-hydrogen gas led to minimal smoke and oxides of nitrogen emissions, even without utilizing exhaust gas recirculation.

Alireza et al,2019,delves into the impact of adding hydrogen to a Reactivity Controlled Compression Ignition (RCCI) natural gas/dimethyl-ether (DME) engine, with a specific focus on combustion characteristics and emissions. The investigation explores different percentages of hydrogen (ranging from 0% to 50%) to understand their effects.

The findings reveal that the introduction of hydrogen brings about a notable increase in total gross work, reaching up to a 19.7% boost when 50% hydrogen is added. Similarly, there's a rise in cumulative heat release, showing a 15.9% increase with 50% hydrogen.

The combustion process experiences advancements as well—combustion start is shifted earlier by approximately 5 crank angle degrees (CAD) with the use of 50% hydrogen, and the burn duration shortens by about 6 CAD. Additionally, the study observes a reduction in released carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions, with decreases of 5.5 grams/kilowatt-hour (gr/kWh) and 9.7 gr/kWh, respectively, when 30% hydrogen is introduced.

Venkateswarlu et al,2015,aims to boost the use of hydrogen (H2) energy in a compression ignition (CI) engine operating in dual-fuel mode. The approach involves adopting two low-temperature combustion (LTC) strategies: delayed pilot fuel injection timing and water injection. The experiments include traditional strategies like diesel dual-fuel mode (DDM) and B20 dual-fuel mode (BDM), alongside LTC strategies such as delayed injection timing dual-fuel mode (RDM) and water-injected dual-fuel mode (WDM).

The results highlight a significant increase in H2 energy share, jumping from 18% with the conventional DDM to 24% and 36% with RDM and WDM, respectively. As the H2 energy share rises in dual-fuel operation, there is a corresponding improvement in energy efficiency. However, at a specific energy share of 18% H2, the energy efficiency decreases from 34.8% with DDM to 33.7% with BDM, 32.7% with WDM, and 29.9% with RDM.

Eris et al 2010,delves into the performance aspects of dual fuel systems in HCCI (Homogeneous Charge Compression Ignition) engines, with a specific focus on incorporating hydrogen as a fuel additive.

It sheds light on the intricate nature of the combustion process within dual fuel systems, emphasizing the interactions between mixing and chemistry occurring inside the combustion chamber during the latter part of the compression stroke and the ignition process.

The paper recognizes the significant challenge of controlling auto-ignition in HCCI, particularly in managing abrupt pressure increases within the cylinder that can impact both performance and emissions.

In exploring the use of hydrogen as a fuel additive in internal combustion engines, the authors conduct a thorough review, considering its effects on both performance and emissions.

Jungsoo et al,2018,conducts a numerical analysis to explore how hydrogen impacts the combustion of biogas in HCCI (Homogeneous Charge Compression Ignition) engines. The focus is on understanding how varying the excess air ratio and hydrogen content influences cylinder pressure, nitric oxide (NO), and carbon dioxide (CO2) emissions.

The study employs the GRI 3.0 mechanism as the foundational model for HCCI combustion calculations. This mechanism provides a detailed representation of the reactions involved in methane combustion and oxidation.

The findings indicate that introducing hydrogen into the HCCI engine results in increased NO emissions but a reduction in CO2 emissions. Additionally, there's an observed rise in cylinder pressure, and the lean operation limits of the engine are extended.

Ayatallah ,at el 2015,explores the combustion characteristics, performance, and exhaust emissions of a Reactivity Controlled Compression Ignition (RCCI) engine fueled with compressed natural gas (CNG) and biodiesel. The focus is on comparing the dual fuel modes of CNG/biodiesel and CNG/diesel, especially under high engine loads.

The findings reveal that employing waste fish oil biodiesel as a high reactivity fuel in the CNG/biodiesel dual fuel mode results in higher in-cylinder pressure and a shorter duration of heat release rate compared to conventional combustion. Notably, the CNG/biodiesel dual fuel mode displays enhanced stability with minimal cycle-to-cycle variations in comparison to CNG/diesel.

Furthermore, the CNG/biodiesel dual fuel mode exhibits higher gross thermal efficiency and lower combustion loss across all engine loads compared to the CNG/diesel mode. While CO emission concentration in CNG/biodiesel mode matches conventional combustion levels at high engine loads, unburned hydrocarbon (UHC) emissions are reduced by approximately 32.5% compared to CNG/diesel. Although NOx emissions are higher for CNG/biodiesel, they still remain significantly lower than conventional combustion with diesel or biodiesel fuels.

Yacine at el ,2021,delves into the impact of adding hydrogen to PRF-85 in an HCCI engine, employing both numerical modeling and a multi-zone model for analysis. The focus extends to understanding the chemical and dilution effects of hydrogen enrichment on combustion characteristics.

The study utilizes a sequential approach, combining a fluid mechanics code with a multi-zone HCCI model. This allows for the determination of temperature and mass distributions, as well as the calculation of combustion and engine efficiency.

The results reveal that the hydrogen dilution effect plays a crucial role in retarding combustion phasing, reducing combustion duration and specific fuel consumption, and enhancing engine thermal efficiency. Conversely, the chemical effect exhibits opposite trends.

Norhidayah,at el,2021,aims to identify the optimal conditions for hydrogen combustion in an argon-oxygen atmosphere and extends the investigation to include all noble gases. The objective is to provide valuable data for predicting hydrogen ignitability under varied conditions. The simulations are conducted using Converge CFD software, with parameters based on the Yanmar NF19SK direct injection CI engine. The results are cross-verified with experimental data obtained from a rapid compression expansion machine (RCEM) operating in an argon-oxygen atmosphere.

The key findings suggest that hydrogen ignition in an argon atmosphere necessitates a minimum initial temperature of 340 K, but combustion tends to be slightly unstable. Helium and neon prove to be suitable options for hydrogen combustion in low compression ratio engines, whereas krypton and xenon require temperature adjustments and a higher compression ratio for stable ignition. The paper concludes by emphasizing the need for detailed parameter recommendations to enhance hydrogen ignitability in conventional diesel engines with minimal modifications.

Alireza K at el, 2018,employed computational fluid dynamic modeling to explore the impact of adding hydrogen in an RCCI CNG/Diesel engine. The inclusion of hydrogen was found to enhance the combustion process, improve engine performance, and reduce emissions.

Hadi at, el, 2020, in this paper is to increase the proportion of hydrogen energy in an RCCI engine that runs on a mixture of natural gas and diesel oil. This is achieved by progressively introducing hydrogen or syngas mixed with exhaust gas recirculation. According to simulation results, incorporating hydrogen into natural gas raises the hydrogen energy share by as much as 40.43%, with only a minimal decrease in engine power output. Similarly, the addition of syngas increases the hydrogen energy share by up to 27.05%, accompanied by a more than 4% improvement in engine power. Moreover, both strategies lead to a notable reduction in hydrocarbon fuel consumption per cycle, showing decreases of up to 46.60% and 33.86%, respectively.

The RCCI combustion, fueled with natural gas, diesel oil, and either hydrogen or syngas, achieves a gross indicated efficiency exceeding 50%. Importantly, this configuration significantly lowers engine emissions compared to RCCI combustion relying solely on natural gas and diesel oil.

Mehmet A at el, 2020,explores how adding hydrogen influences the performance and emissions of a compression ignition (CI) engine using a mix of diesel fuel and waste cooking oil biodiesel (WCOB). The experiments were carried out on a four-cylinder, turbocharged CI engine, maintaining a constant speed while varying engine loads.

The results reveal positive effects of hydrogen addition on break specific fuel consumption (BSFC) across all tested conditions. The introduction of hydrogen led to increased exhaust gas temperatures (EGTs) and cylinder pressures (CPs). Notably, at lower engine loads, the emissions of NOx and total hydrocarbon (THC) decreased with hydrogen addition, but these emissions increased at higher loads. Concurrently, carbon dioxide (CO2) and oxygen (O2) emissions decreased, while smoke emissions rose.The study identifies the optimal hydrogen addition rate as 30 liters per minute.

Mohammad at el 2022,in this paper thoroughly explores the promising potential of hydrogen as a cleaner alternative to traditional fossil fuels. It effectively underscores the versatility of hydrogen (H2) due to its high calorific value, clean-burning nature, and abundant availability from various feedstocks, making it a suitable contender in addressing environmental concerns. A notable focus is placed on the different colors of hydrogen production—green, blue, and turquoise. These colors signify diverse production methods, with green hydrogen sourced from renewable energy, blue hydrogen incorporating carbon capture, and turquoise hydrogen using methane pyrolysis. The paper emphasizes the importance of a carbon capture scheme and clean hydrogen production methodologies in ensuring the environmental sustainability of hydrogen as a fuel. Overall, the review provides valuable insights into hydrogen's potential and the varied production approaches that can contribute to a more sustainable energy future.

R, Balasubramanian at el,2022,delves into the intriguing realm of hydrogen's thermodynamic behavior and its diverse applications across industries, though it does not explicitly discuss hydrogen as an alternative fuel source. The primary objective of the study is to ascertain the second virial coefficient of hydrogen and its isomers. Impressively, the obtained results align closely with existing correlations in the high-temperature range, showcasing the reliability of the findings. While the paper doesn't explicitly advocate for hydrogen as an alternative energy source, it hints at hydrogen's potential in various industries. The focus on determining the second virial coefficient adds depth to our understanding of hydrogen's thermodynamic characteristics, contributing valuable insights that may have implications for its applications beyond the scope of this study. Overall, the paper offers a meticulous exploration of hydrogen's behavior, opening avenues for further research and potential applications in diverse industrial settings.

Timur, B et al,2022,This paper intriguingly explores the potential of hydrogen as an alternative fuel source, hinting at its viability without explicitly stating its suitability. The notion that hydrogen can serve as an ideal alternative fuel with a zero carbon footprint adds a layer of optimism to the discussion. However, the paper pragmatically acknowledges the existence of technical challenges that must be addressed for the widespread industrial use of hydrogen. This dual perspective—highlighting the promising environmental aspects while recognizing the practical hurdles—offers a balanced view. The call to solve technical problems emphasizes the need for further research and innovation to fully harness the benefits of hydrogen as an alternative fuel. Overall, the paper stimulates contemplation on the potential role of hydrogen in addressing environmental concerns, while also underscoring the importance of overcoming practical obstacles for its successful implementation in industrial settings.

Luiz et al, 2022, this paper presents a compelling exploration into the suitability of hydrogen as an alternative fuel, emphasizing its application in both fuel cells and as a fuel additive for internal combustion engines. The acknowledgment of hydrogen as a promising alternative to traditional fossil fuels, with the added benefit of reducing CO2 emissions, underscores its potential significance in addressing environmental concerns. The focus on hydrogen's versatility, particularly as a fuel additive in internal combustion engines, adds practicality to the discussion. The literature review approach of the paper provides a comprehensive overview of hydrogen's role as an energy source, concentrating specifically on its use as a fuel additive and as a potential replacement for fossil fuels. The inclusion of synthetic fuels as another promising alternative to meet energy demand broadens the scope, reflecting a holistic examination of alternative energy solutions. Overall, the paper not only contributes to the understanding of hydrogen's diverse applications but also positions it within the broader context of addressing the evolving energy landscape.

Concusion:

These research papers collectively showcase the promising role of hydrogen in internal combustion engines. The studies explore diverse applications, including reactivity-controlled dual fuel engines, ammonia-fueled engines, and hydrogen addition in various combustion modes. The findings highlight improved efficiency, reduced emissions, and the potential for cleaner combustion processes. Overall, hydrogen emerges as a versatile and impactful additive for advancing sustainable engine technologies.

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