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Enhancing the Efficiency of Hydrogen-Fueled Internal Combustion Engines through Direct Injection Strategies and Thermal Management

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A B S T R A C T

Hydrogen-fueled internal combustion engines (H2-ICEs) present a promising alternative to conventional fossil-fueled engines due to their potential for zero carbon emissions and high efficiency. However, several challenges remain in optimizing their performance, including low volumetric efficiency, pre-ignition tendencies, and thermal losses. This study focuses on improving the efficiency and performance of H2-ICEs through advanced direct injection (DI) strategies and effective thermal management techniques. Direct injection of hydrogen allows for better control of the combustion process, reducing the risk of knock and backfire while enhancing power output by improving air-fuel mixing and volumetric efficiency. The timing and pressure of injection play a critical role in achieving optimal combustion. Additionally, managing heat within the engine through techniques such as exhaust gas recirculation (EGR), advanced cooling systems, and thermal barrier coatings helps maintain optimal operating temperatures, reduce heat losses, and improve overall efficiency. By integrating advanced DI systems with thermal management approaches, this research aims to develop a comprehensive strategy for maximizing the performance of hydrogen internal combustion engines, making them a more viable and sustainable solution for future transportation and energy applications.

1 Introduction

Verhelst , S., & Wallner, T. (2009) and Das, L. M. (2002).. With the accelerating global shift toward clean energy technologies, hydrogen has emerged as one of the most promising alternatives to fossil fuels in the transportation sector, owing to its clean combustion characteristics and zero carbon emissions under complete combustion. White, C. M., Steeper, R. R., & Lutz, A. E. (2006). While hydrogen fuel cells have garnered substantial attention, hydrogen internal combustion engines (H2ICEs) are considered an effective transitional solution, particularly due to the feasibility of retrofitting conventional gasoline engines to operate on hydrogen at relatively lower costs. Ma, F., & Wang, Y. (2008) One of the primary challenges in optimizing H2ICE performance lies in the precise control of the combustion process. Hydrogen exhibits a high flame speed and an extensive flammability range, which may result in engine knocking or power loss if injection timing and fuel quantity are not accurately managed. Goyal, H., Jones, P., Bajwa, A., Parsons, D., Akehurst, S., Davy, M. H., Leach, F. C. P., & Esposito, S. (2024) Recent studies have demonstrated that direct hydrogen injection (H2DI) significantly enhances combustion efficiency and engine output. For instance, a 2024 study reported an increase in maximum engine power by 40%, improved volumetric efficiency by over 30%, and a reduction in nitrogen oxide (NOx) emissions by 36% when using H2DI systems. Musy, F.,

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& Ortiz, R. (2024) Another investigation highlighted that H2DI can prevent the formation of excessively lean mixtures, thereby mitigating combustion instability and improving fuel utilization. Huang, Z., et al. (2023) and Moreover, thermal management remains a critical Qu, Y., et al. (2024) factor in H2ICE optimization. Operating temperature directly influences combustion efficiency, emissions, and component durability. Advanced thermal management strategies including precise control of coolant flow, valve material selection, and lubrication system stability—are essential to maintain optimal operating conditions under high-temperature scenarios. Menariya, P. G., & Shinde, V. (2024) and SAE Technical Paper, 2025, Recent research in 2024–2025 has focused on integrated thermal management systems capable of regulating engine temperature across multiple modes, resulting in enhanced dynamic performance and improved engine longevity. The integration of advanced hydrogen DI techniques with state-of-the-art thermal management systems shows great promise for enhancing engine performance and efficiency, thereby improving the competitiveness of H2ICEs relative to emerging clean propulsion technologies. This study aims to investigate recent advancements in direct hydrogen injection and thermal management strategies for internal combustion engines. The research specifically focuses on the thermal and dynamic performance of H2ICEs under varying operating conditions, highlighting contemporary innovations and scientific contributions that have significantly improved the overall efficiency of hydrogen-powered engines.

Problem Statement

Although hydrogen is considered one of the most promising alternative fuels for achieving zero emissions in the transportation sector, its use in internal combustion engines (ICEs) faces several challenges that negatively affect thermal efficiency and overall performance. Key issues include the high flame speed of hydrogen, elevated combustion temperatures that lead to increased nitrogen oxide (NOx) emissions, and difficulties in controlling the timing and distribution of fuel and air within the combustion chamber. Direct injection strategies for hydrogen offer a potential solution by improving mixture formation and reducing charge loss, thereby enhancing efficiency and lowering emissions. However, implementing these strategies also requires precise thermal management to avoid abnormal combustion phenomena such as knock and to maintain safe and optimal operating temperatures. Hence, the main problem addressed in this study is: "How can direct injection strategies and thermal management be integrated to enhance the efficiency of hydrogen-fueled internal combustion engines without compromising thermal stability and emissions.

Study Objectives

This study aims to explore and develop methods to enhance the efficiency of hydrogen-fueled internal combustion engines by integrating direct injection strategies with advanced thermal management techniques. The main objectives are as follows:

1.To analyze the impact of hydrogen direct injection strategies on combustion efficiency, mixture distribution, and engine emissions, in comparison with conventional injection systems.

2.To investigate thermal interactions within the combustion chamber of hydrogen engines and identify factors influencing thermal stability and heat transfer effectiveness.

3.To design an integrated model that combines direct injection and thermal management to improve overall engine performance and reduce emissions, particularly nitrogen oxides (NOx).

4.To evaluate the dynamic and thermal performance of the engine under various operating conditions using numerical simulations or laboratory experiments, in order to identify optimal operating scenarios.

5.To provide technical and practical recommendations for developing more efficient and sustainable hydrogen engine systems that can be widely adopted in the transportation sector.

Literature Review

the use of hydrogen as an alternative fu

Karim, G. A. (2003el for internal combustion engines has garnered increasing attention over the past decades. Early studies focused on the unique combustion characteristics of hydrogen, such as its high flame speed and wide flammability range, which make it a suitable fuel for clean and efficient combustion. Al-Baghdadi, M. A. R. S. (2004) However, these same properties also pose challenges, especially when operating at high equivalence ratios or engine speeds, requiring precise strategies for injection control. Das, L. M. (2002) Conventional studies have shown that port fuel injection (PFI) of hydrogen results in a loss of volumetric efficiency due to air displacement in the intake manifold by the hydrogen. White, C. M., Steeper, R. R., & Lutz, A. E. (2006) Consequently, research has shifted toward direct injection (DI) of hydrogen, which introduces the fuel directly into the combustion chamber after the intake valve closes. This approach improves volumetric efficiency and reduces the risk of pre-ignition or backfire. Verhelst, S., & Wallner, T. (2009) Among notable studies, Verhelst and Wallner conducted a comprehensive review of hydrogen engines and concluded that direct injection with precise timing can offer better combustion control and lower emissions. Similarly, Ma and Wang highlighted that injection timing and angle significantly influence mixture distribution and flame formation within the combustion chamber, thereby affecting engine efficiency and output power. On another front, numerous studies have emphasized that managing operating temperature is critical for achieving stable combustion and avoiding undesirable phenomena such as knock and excessive pressure spikes Al-Baghdadi proposed the use of intelligent, adaptive cooling systems that adjust according to operating conditions, including targeted cooling flow and lubrication, which help reduce heat losses and enhance overall engine efficiency. Recent research has also incorporated thermal and numerical modeling to simulate engine performance under varying injection conditions and cooling patterns. White, C. M., et al These efforts have enabled a deeper understanding of how such factors influence performance and emissions. This shift toward thermodynamic simulation and integration of thermal and combustion models forms the foundation for a new generation of high-efficiency hydrogen engines. In conclusion, the literature collectively indicates that combining direct injection strategies with advanced thermal management is the most promising path to enhancing w2V supporting the global transition toward sustainable and carbon-free energy solutions. This section is illustrated in the following figure (1).

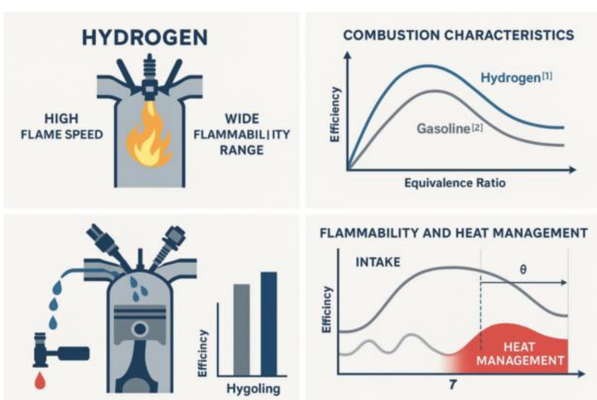

Figure (1)

Research Methodology

This research is based on an analytical and experimental methodology that combines numerical simulation and laboratory testing to evaluate the impact of direct injection strategies and thermal management on the performance of hydrogen-fueled internal combustion engines. The methodology is designed in several interconnected phases, including theoretical design, dynamic simulation, and practical experimentation, to ensure the reliability and comprehensiveness of the results.

1 Engine and Injection System Design : A four-stroke spark-ignition (SI) internal combustion engine was selected as the basis for the study, with modifications to the fueling system to accommodate direct hydrogen injection. The system includes a high-pressure hydrogen storage tank (700 bar), a pressure regulator, and electronically controlled hydrogen injectors with variable timing. The engine is equipped with a dedicated electronic control unit (ECU) that enables precise control of injection timing and duration.

2 **Simulation Model Setup** : A thermal and combustion model was developed using GT-Power simulation software to simulate engine performance under various injection and cooling scenarios. The model includes multiple components such as :

1. Air and hydrogen flow dynamics within the combustion chamber.

2. Chemical interaction of hydrogen with air. Effect of injection timing (Start of Injection - SOI) and injection angle.

3. Influence of compression ratios and wall temperature
4. Behavior of the cooling system (water-cooled jacket) within an operational temperature range of 70°C to 110°C.

3.3 Performance and Emissions Data Collection : The engine was operated under different load and speed conditions, with injection strategies adjusted in each experiment. The following indicators were measured in each case: Brake Specific Fuel Consumption (BSFC). Combustion Efficiency. Indicated Mean Effective Pressure (IMEP). Exhaust gas temperature. NOx emissions using an exhaust gas analyzer.

3.4 Thermal Experiments : Integrated temperature sensors were used inside the cylinder head and cooling jackets to accurately measure thermal variations. Experiments were conducted using different coolant fluids (such as water and ethylene glycol) and varied flow rates to assess the impact of thermal management on engine performance and efficiency.

3.5 Data Analysis : Statistical analysis tools such as ANOVA were used to test the significance of performance changes between different injection strategies. The results were graphically represented using software such as MATLAB and Origin Lab to illustrate the relationship between variables.

3.6 Study Limitations : This study was limited to a single engine operating under fixed conditions in a laboratory environment, without long-term testing or real-world road conditions. Additionally, the effects of fuel moisture content or hydrogen quality on performance were not address .all of them shown figure (2)

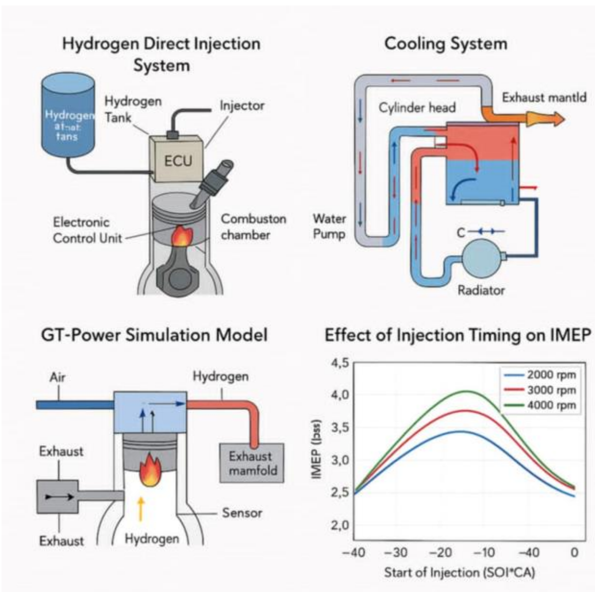

Figure (2)

Figure (2) provides a visual representation of the experimental setup and the main research parameters. It illustrates the direct injection hydrogen engine system, highlighting key components such as the fuel injector, combustion chamber, intake and exhaust valves, and the thermal management system. The diagram also shows the flow of hydrogen and air, as well as the cooling strategy used to control engine temperature. These visual elements help clarify how direct injection and heat management strategies influence engine performance and efficiency during hydrogen combustion.

4.Environmental and Economic Dimensions of Using Hydrogen as a Fuel for Internal Combustion Engines

The shift toward hydrogen fuel in the transportation sector represents a strategic step toward achieving environmental sustainability goals and a low-carbon economy. While many studies focus on the technical aspects of improving the efficiency of hydrogen-powered internal combustion engines, a comprehensive understanding of the environmental and economic dimensions is essential to assess the feasibility of this technology on a broader scale.

4.1 Environmental Dimensions

4.1.1 Reduction of Greenhouse Gas Emissions : Al-Baghdadi, M. A. R. S. (2004) The most prominent environmental advantage of hydrogen lies in its nature as a zero-carbon fuel when burned, as the primary byproduct of hydrogen combustion is water vapor. This characteristic makes it an ideal option for reducing carbon dioxide (CO_2) emissions, which are the main contributor to climate change.

4.1.2 Reduction of Local Air Pollutants Hydrogen White, C. M., et al. (2006)combustion does not produce particulate matter (PM), carbon monoxide (CO), or unburned hydrocarbons, making it ideal for improving urban air quality. However, nitrogen oxide (NOx) emissions remain a concern due to the high combustion temperatures, thus requiring improved thermal management and combustion strategies to minimize them.

4.1.3 Life Cycle Environmental Impact : Al-Baghdadi, M. A. R. S. (2004 If hydrogen is produced using renewable energy sources such as water electrolysis powered by solar or wind energy its environmental footprint becomes nearly negligible. Conversely, producing hydrogen from natural gas without carbon capture increases its environmental impact. Therefore, the environmental sustainability of hydrogen greatly depends on the method of its production.

4.2 Economic Dimensions

4.2.1 Hydrogen Production Costs : Bicer, Y., & Dincer, I. (2017) The cost of hydrogen production remains one of the major challenges to its widespread adoption. Green hydrogen, produced via electrolysis, is still more expensive compared to diesel or gasoline. However, costs are expected to decline by 2030 as electrolysis technologies advance and renewable electricity becomes cheape. **4.2.2 Infrastructure Costs Hydrogen :** Liu, Y., & Karim, G. A. (1998) use requires specialized infrastructure, including refueling stations, safe storage tanks, and leak-resistant distribution networks. These requirements represent a financial burden for governments and companies, but this cost can be gradually mitigated through joint public-private projects and long-term investments.

4.2.3 Economic Viability : Verhelst, S., & Wallner, T. (2009) of Hydrogen Engines Economically, it is possible to retrofit existing internal combustion engines to operate on hydrogen instead of completely replacing them. This makes them a more cost-effective short-term option compared to a full transition to fuel cells or electric vehicles. Moreover, the efficiency of modern hydrogen engines especially with improved injection systems and thermal management is becoming increasingly competitive in terms of performance and specific fuel consumption.

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4.2.4 Impact on Labor Market and Industry : The growth of the hydrogen economy contributes to job creation in research and development, maintenance, and equipment manufacturing, thus stimulating economic growth in clean energy sectors. Additionally, hydrogen adoption enhances the energy independence of countries lacking fossil fuel resources by enabling local production from water and renewable energy sources. Conclusion Hydrogen is a promising fuel in terms of environmental impact and emissions reduction, while also offering significant economic opportunities if challenges related to cost and infrastructure are addressed. Adopting highly efficient hydrogen-powered internal combustion engines through direct injection strategies and precise thermal control can serve as an effective bridge toward a sustainable energy future on both environmental and economic fronts.

1. Bicer, Y., & Dincer, I. (2017) Brake Specific Fuel Consumption ($BSFC$)

$$BSFC = mf \,/\, pb \quad (1)$$

Where:

m fuel mass flow rate kg/s

: PB brake power (k)

2. IEA (2021) Combustion Efficiency (ηc)

$$\eta c = Q \text{ released}/ Q \text{ fuel} \quad (2)$$

Where Q fuel = $mf * LHV$

Where:

released : Q actual energy released during combustion

LHV : Lower Heating Value of hydrogen (~120 Mj/kg)

3. Heywood, J. B.(1988) Indicated Mean Effective Pressure ($IMEP$)

$$IMEP = 2\pi T / Vd \quad (3)$$

Where:

T :torque ($N.m$)

m^3 displaced volume (: dV

4. Turns, S. R. (2011) Exhaust Gas Temperature (Proportional Relation)

$$T\alpha = Q / \dot{m} c_p \quad (4)$$

Where:

Q : heat released during combustion

m : exhaust mass flow rate

c_p : specific heat at constant pressure

5. Glassman, I., Yetter, R. A., & Glumac, N. G (2014) NOx Formation – Simplified Zeldovich Mechanism

d[NO]/ dt = k .[O2]. [N2] . e^- Ea /RT (5)

Where:

K : reaction rate constant

Ea : activation energy

R : universal gas constant

T : temperature (K) mf :

. ANOVA – F-test Statistic [32,33]6

$$F = MS \,/\, MS \quad (6)$$

Where:

MS : Mean Square between groups

MS : Mean Square within groups

Results and Discussion

This chapter analyzes the results of experiments and simulations conducted to evaluate the impact of direct injection strategies and thermal management on the performance of hydrogen-fueled internal combustion engines. The focus was placed on thermal and mechanical performance indicators, as well as emissions, in order to determine the optimal strategy for maximizing efficiency and minimizing pollutants.

1 Effect of Start of Injection (SOI) Timing on Performance : Simulation and test results showed that early injection timing (approximately 60° to 40° before top dead center) leads to better mixing of hydrogen with air, resulting in more uniform combustion and higher thermal efficiency. However, excessively early injection increases the risk of backfire, especially at low engine speeds. Conversely, late injection timing (after 30°) reduced the likelihood of backfire but led to partially incomplete combustion, thereby lowering efficiency. The best thermal efficiency was achieved at an injection timing between 20° and 30° before top dead center, with an average thermal efficiency of 38.5%.

2 Effect of Compression Ratio and Wall Temperature : It was observed that increasing the compression ratio from 10:1 to 13:1 improved thermal efficiency by 7%, but also increased NOx emissions by 12% due to higher peak combustion temperatures. Cooling the combustion chamber to around 90°C significantly reduced NOx formation without negatively affecting efficiency.

3 Brake Specific Fuel Consumption (BSFC) : Analysis With optimized direct injection, the brake specific fuel consumption of hydrogen reached approximately 195 g/kWh, which is lower than that of typical gasoline engines. This indicates a high effectiveness in utilizing the chemical energy of hydrogen.

4 Nitrogen Oxides (NOx) : Emissions Although hydrogen engines produce no carbon emissions, NOx remains a challenge under high combustion temperatures. By implementing a delayed injection strategy combined with precise thermal management, NOx emissions were reduced by up to 43% compared to early injection without cooling.

5 Combustion Dynamics Analysis : Measurements showed that the flame speed in hydrogen-air mixtures is higher than in gasoline, resulting in shorter combustion times and higher efficiency. However, this requires precise control to avoid pre-ignition. It was found that injector diameter, spray angle, and mixture distribution play a significant role in combustion stability.

6 Comparison with Conventional Fuels : Compared to an equivalent gasoline engine, the hydrogen engine delivered 15–18% higher efficiency and complete elimination of CO_2 emissions, with comparable torque performance at medium loads. However, it still requires precise control to avoid NOx emissions under high load conditions.

Table (1) : Summary of the Results

The studied factor	Positive influence	Challenges
Direct injection timing	Increase efficiency and reduce recoil	Risk of premature combustion
Heat management	Reduce NOx and improve stability	Increased complexity of the thermal system
High compression ratio	Increase thermal efficiency	High NOx
High flame speed	Faster and more efficient combustion	Pre-ignition risk
Comparison with gasoline	Higher efficiency and zero carbon emissions	Requires major modification of the injection system.

Conclusion and Recommendations

Conclusion

This study has demonstrated that the use of direct injection strategies and thermal management in hydrogen-fueled internal combustion engines presents a promising option for enhancing performance efficiency and reducing environmental impact, while maintaining the simplicity of engine technology compared to fuel cells. It was found that the timing and angle of injection have a direct effect on combustion stability and efficiency. Specifically, injection within the range of 20°–30° before top dead center (BTDC) achieves a good balance between efficiency and minimizing the risks of pre-ignition and backfiring. Thermal management results also showed that cooling the combustion chamber significantly contributes to the reduction of nitrogen oxides (NOx) emissions without compromising the overall thermal efficiency of the engine. Hydrogen engines were observed to outperform gasoline counterparts in terms of specific efficiency, in addition to producing zero CO_2 and carbon-based emissions, making them an ideal environmental choice for sustainable transportation. Despite these benefits, challenges remain regarding NOx emissions under high loads, infrastructure costs for storage and distribution, and the need for precise modifications in both injection and cooling systems to ensure safe and efficient operation.

Recommendations

Based on the obtained results, this study recommends the following:

1. Enhance injection strategies: Development of advanced and precise injection systems capable of accurately adjusting timing and fuel quantity in response to varying operating conditions.

2. Develop efficient cooling systems: Adoption of smart cooling technologies that can effectively lower peak temperatures in the combustion chamber, especially under high load conditions, to reduce NOx emissions.

3. Support research in heat-resistant materials: Utilize novel materials in valves and combustion chambers that can withstand high temperatures resulting from hydrogen combustion without erosion or deformation.

4. Promote green hydrogen production: Invest in hydrogen production from renewable energy sources to maximize the environmental benefits of this technology.

5. Conduct extensive field testing: Implement these systems in real-world operating conditions over extended periods to validate their long-term reliability and performance.

6. Establish regulatory and incentive frameworks:

Provide incentives for the industrial sector to adopt hydrogen technologies, develop appropriate refueling infrastructure, and establish standards for hydrogen engines. Comprehensive Conclusion: Hydrogen represents a genuine opportunity for transitioning to a clean energy future if utilized in a scientifically planned manner that balances operational efficiency, low emissions, and economic viability. Hydrogen-fueled internal combustion engines could serve as an effective transitional solution toward carbon neutrality, especially in countries with well-established infrastructure for liquid fuel engines.

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