

Combustion and Emission Characteristics of Hydrogen-Assisted Diesel Engines under Dual-Fuel Operation

Saket S. Patil¹, Dr. Krishna Shri Ramkrishna Shrivastava²

¹ Research Student, Department of Mechanical Engineering, SSBTCOET, Bambhori Jalgaon, Maharashtra, India

² Associate Professor, Department of Mechanical Engineering, SSBTCOET, Bambhori Jalgaon, Maharashtra, India

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ABSTRACT

The increasing demand for clean and sustainable energy sources has intensified research on hydrogen utilization in compression ignition engines. Hydrogen used as a supplementary fuel in diesel engines offers the potential to improve combustion efficiency and reduce carbon-based emissions. This paper presents a comprehensive review of hydrogen-enriched diesel engine operation under dual-fuel and common rail direct injection modes focusing on performance characteristics, emission behavior and engine control strategies. Various experimental studies indicate that hydrogen enrichment enhances brake thermal efficiency and reduces brake specific fuel consumption due to its high flame speed and superior combustion characteristics. Significant reductions in carbon monoxide, unburned hydrocarbons and carbon dioxide emissions have been reported owing to the carbon-free nature of hydrogen. However, an increase in nitrogen oxide emissions remains a critical challenge due to elevated in-cylinder temperatures. The application of exhaust gas recirculation and optimized injection strategies has been identified as an effective approach for mitigating NOx emissions without compromising engine performance. Furthermore, the combination of hydrogen with biodiesel and alcohol-based fuels improves fuel sustainability while maintaining engine stability. Advances in common rail direct injection technology provide enhanced control over injection pressure and timing making CRDI engines highly suitable for hydrogen dual-fuel operation. An environmental and policy perspective, hydrogen aligns with global clean energy goals and alternative fuel regulations. Despite promising results, challenges related to hydrogen storage and long-term engine durability. This study highlights existing research gaps and emphasizes the need for advanced control strategies and real-world performance evaluation to facilitate the large-scale adoption of hydrogen-assisted diesel engines.

Keywords:- Hydrogen-assisted combustion, Dual-fuel diesel engine, Combustion characteristics, Emission control, Exhaust gas recirculation, Alternative fuels

1. INTRODUCTION

Diesel engines remain indispensable in transportation, agricultural machinery, marine propulsion and distributed power generation because of their superior fuel economy, durability and load-handling capability. However, conventional diesel combustion is associated with significant emissions of carbon monoxide (CO), unburned hydrocarbons (HC), particulate matter (PM), and nitrogen oxides (NOx) which contribute to air pollution and climate change [1]. Stringent emission regulations and growing concerns over fossil fuel depletion have encouraged researchers to explore alternative and cleaner fuel options that can be integrated with existing engine platforms.

Hydrogen has emerged as a promising energy carrier due to its high gravimetric energy density, wide flammability range and absence of carbon in its molecular structure [8,9]. When used in internal combustion engines, hydrogen offers the potential to significantly reduce carbon-based emissions while improving combustion efficiency. However, the direct replacement of diesel with hydrogen in compression ignition engines is challenging due to hydrogen's high auto-ignition temperature. As a result, hydrogen is commonly employed in dual-fuel mode, where diesel acts as the pilot fuel and hydrogen contributes to the main energy release [1,11].

Numerous experimental investigations have demonstrated that hydrogen enrichment improves combustion characteristics and engine performance. At the same time, increased NOx emissions and combustion instability at higher hydrogen flow rates remain major technical challenges [9,10]. This paper provides an in-depth review

of combustion behavior, performance and emission characteristics of hydrogen-assisted diesel engines operating under dual-fuel conditions.

1.1 Hydrogen Utilization in Diesel Engines

Hydrogen can be introduced into diesel engines through intake manifold induction, port injection or direct in-cylinder injection. Intake manifold induction is the most commonly adopted technique due to its simplicity and minimal engine modification requirements [1]. Hydrogen mixes with intake air and participates in combustion once ignition is initiated by diesel injection. Chintala and Subramanian [1] reported that hydrogen enrichment leads to faster flame propagation shorter combustion duration and reduced ignition delay. Tsujimura and Suzuki [11] observed stable combustion under hydrogen–diesel dual-fuel operation when hydrogen flow rates were maintained within safe limits. Verma et al. [9] emphasized that hydrogen produced from renewable sources can significantly enhance the sustainability of diesel engines without requiring complete engine replacement.

1.2 Hydrogen Combined with Biodiesel and Alcohol Fuels

The combined use of hydrogen with biodiesel and alcohol fuels has gained attention as it further reduces dependency on petroleum-based fuels. Biodiesel fuels offer oxygenated molecular structures that improve combustion efficiency, while hydrogen enhances flame speed and combustion completeness. Parthasarathy et al. [2] demonstrated improved performance and emission characteristics when hydrogen was used with ethanol–biodiesel blends in a direct injection diesel engine. Rajak et al. [3] reported lower emissions and improved efficiency using hydrogen-enriched microalgae biodiesel and n-butanol blends. Shrivastava et al. [4] optimized biodiesel–ethanol–diesel blends and observed enhanced brake thermal efficiency and reduced emissions.

2. COMBUSTION CHARACTERISTICS OF HYDROGEN-ASSISTED DIESEL ENGINES

Hydrogen enrichment significantly influences in-cylinder combustion phenomena such as ignition delay, heat release rate and peak cylinder pressure. The high flame speed of hydrogen accelerates combustion resulting in more complete fuel oxidation [1,11]. Hydrogen-assisted combustion typically exhibits a higher premixed combustion phase due to improved air–fuel mixing. This leads to increased peak cylinder pressure and higher heat release rates particularly at higher engine loads [9]. However, excessive hydrogen induction may result in knocking or backfiring if combustion control strategies are not properly implemented

2.1 Heat Release Rate and Cylinder Pressure

Experimental studies indicate that hydrogen enrichment increases the rate of heat release due to rapid flame propagation [10]. Saravanan et al. [10] reported that hydrogen-assisted diesel combustion produces higher peak cylinder pressure compared to conventional diesel operation. These effects contribute to improved thermal efficiency but also elevate combustion temperatures which directly influence NO_x formation.

3. ENGINE PERFORMANCE CHARACTERISTICS

Hydrogen-assisted diesel engines demonstrate notable improvements in performance parameters such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). The enhanced performance is primarily attributed to improved combustion efficiency and partial replacement of diesel fuel [1,9].

3.1 Brake Thermal Efficiency

Hydrogen enrichment increases BTE due to reduced ignition delay and faster combustion. Khandal et al. [7] reported significant efficiency improvement in CRDI engines at optimized hydrogen flow rates and injection pressures. Khan et al. [12] observed similar improvements when hydrogen was combined with Ceiba Pentandra biodiesel. Alçelik et al. [5] confirmed that hydrogen enrichment improves the performance of indirect injection diesel engines fueled with waste biodiesel blends.

3.2 Brake Specific Fuel Consumption

BSFC decreases with hydrogen supplementation as hydrogen contributes to engine power output while reducing diesel consumption [3,9]. The reduction in BSFC depends on operating parameters such as engine load, hydrogen flow rate and injection timing [7].

4. EMISSION CHARACTERISTICS

Hydrogen-assisted combustion has a significant impact on diesel engine emissions.

4.1 Carbon-Based Emissions

CO, HC and CO₂ emissions are substantially reduced due to the absence of carbon in hydrogen and improved oxidation of diesel fuel [2,3]. Several studies report up to 30–50% reduction in CO and HC emissions under optimized hydrogen flow conditions [1,9].

4.2 Nitrogen Oxide Emissions

Despite reductions in carbon-based NO_x emissions generally increase with hydrogen enrichment due to higher in-cylinder temperatures and enhanced combustion intensity [10,11].

5. ROLE OF EXHAUST GAS RECIRCULATION AND INJECTION STRATEGY

Exhaust gas recirculation (EGR) is one of the most effective techniques for controlling NO_x emissions in hydrogen-assisted diesel engines. EGR reduces oxygen concentration and peak combustion temperature, thereby suppressing thermal NO_x formation [10]. Saravanan et al. [10] demonstrated that combining hydrogen enrichment with EGR significantly reduces NO_x emissions while maintaining acceptable performance. Gu and Su [6,14] highlighted that optimized injection strategies coupled with EGR improve transient engine performance. Zhang et al. [15] emphasized the combined thermal and chemical effects of EGR on combustion and emission behavior.

6. CRDI ENGINES AND ADVANCED CONTROL STRATEGIES

Common rail direct injection (CRDI) systems provide precise control over fuel injection timing, pressure, and duration. This makes CRDI engines particularly suitable for hydrogen dual-fuel operation. Anandkumar et al. [16] reported improved combustion stability and emission control in CRDI engines with hydrogen induction. Advanced control strategies involving variable injection timing and hydrogen flow modulation are essential for achieving optimal performance and emission reduction.

7. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite promising results, several challenges remain:

- Safe hydrogen storage and onboard handling
- Control of NO_x emissions at high hydrogen flow rates
- Long-term durability of engine components

Future research should focus on artificial intelligence-based engine control, real-world driving cycle analysis and integration with green hydrogen production technologies [8,13].

8. CONCLUSIONS

Hydrogen-assisted diesel engines operating under dual-fuel mode offer a viable pathway toward cleaner and more efficient combustion. Significant improvements in thermal efficiency and reductions in carbon-based emissions have been consistently reported. However, increased NO_x emissions remain a critical challenge, necessitating advanced mitigation strategies such as EGR and optimized injection control. The integration of hydrogen with biodiesel and alcohol fuels further enhances sustainability. With continued technological advancements, hydrogen-assisted diesel engines can play an important role in the transition toward low-emission transportation systems.

9. REFERENCES

- [1] Chintala, V., & Subramanian, K. A. (2017). A comprehensive review on utilization of hydrogen in a compression ignition engine under dual fuel mode. *Renewable and Sustainable Energy Reviews*, 70, 472–491. <https://doi.org/10.1016/j.rser.2016.11.247>
- [2] Parthasarathy, M., Isaac Joshua, J., Lalvani, R. R., Dhinesh, B., & Annamalai, K. (2016). Effect of hydrogen on ethanol–biodiesel blend on performance and emission characteristics of a direct injection diesel engine. *Ecotoxicology and Environmental Safety*, 134, 433–439. <https://doi.org/10.1016/j.ecoenv.2015.11.005>
- [3] Rajak, U., Nashine, P., Verma, T. N., & Pugazhendhi, A. (2020). Performance and emission analysis of a diesel engine using hydrogen enriched n-butanol, diethyl ester, and Spirulina microalgae biodiesel. *Fuel*, 271, 117645. <https://doi.org/10.1016/j.fuel.2020.117645>
- [4] Shrivastava, K., Thipse, S. S., & Patil, I. D. (2021). Optimization of diesel engine performance and emission parameters of Karanja biodiesel–ethanol–diesel blends at optimized operating conditions. *Fuel*, 293, 120451. <https://doi.org/10.1016/j.fuel.2021.120451>
- [5] Alçelik, N., Saridemir, S., Polat, F., & Ağbulut, Ü. (2024). Role of hydrogen enrichment for indirect diesel engine behaviours fuelled with diesel–waste biodiesel blends. *Energy*, 302, 131680. <https://doi.org/10.1016/j.energy.2024.131680>
- [6] Gu, W., & Su, W. (2023). Study on the effects of exhaust gas recirculation and fuel injection strategy on transient process performance of diesel engines. *Sustainability*, 15(16), 12403. <https://doi.org/10.3390/su151612403>

- [7] Khandal, S. V., Khan, T. M. Y., & Kamangar, S. (2021). Effects of hydrogen flow rate, injection pressure, and EGR on performance of CRDI engine. *Fuel and Energy Abstracts*, Emerald Publishing. <https://doi.org/10.1108/FEBE-02-2021-0007>
- [8] International Energy Agency (IEA). (2022). *World Energy Outlook 2022*. International Energy Agency, Paris.
- [9] Verma, A., Suman, A., Das, L. M., Kaushik, S. C., & Tyagi, S. K. (2020). A renewable pathway towards increased utilization of hydrogen in diesel engines. *International Journal of Hydrogen Energy*, 45(8), 5577–5587. <https://doi.org/10.1016/j.ijhydene.2019.05.213>
- [10] Saravanan, N., Nagarajan, G., Kalaiselvan, K. M., & Dhanasekaran, C. (2008). An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique. *Renewable Energy*, 33(3), 422–427. <https://doi.org/10.1016/j.renene.2007.03.015>
- [11] Tsujimura, T., & Suzuki, Y. (2017). The utilization of hydrogen in hydrogen/diesel dual fuel engine. *International Journal of Hydrogen Energy*, 42(19), 14019–14029. <https://doi.org/10.1016/j.ijhydene.2017.01.152>
- [12] Khan, T. M. Y., Soudagar, M. E. M., & Mokashi, I. (2021). Performance of CRDI engine using Ceiba Pentandra biodiesel and hydrogen fuel combination. *Energies*, 14(20), 6504. <https://doi.org/10.3390/en14206504>
- [13] Environmental Protection Agency, U.S. (2024). Alternative fuels. U.S. EPA. <https://www.epa.gov/renewable-fuel-standard-program/alternative-fuels>
- [14] Gu, W., & Su, W. (2023). Study on the effects of exhaust gas recirculation and fuel injection strategy on transient process performance of diesel engines. *Sustainability*, 15(16), 12403. <https://doi.org/10.3390/su151612403>
- [15] Zhang, W., Feng, T., Li, Z., Chen, Z., & Zhao, J. (2021). EGR thermal and chemical effects on combustion and emission of diesel/natural gas dual-fuel engine. *Fuel*, 302, 121161. <https://doi.org/10.1016/j.fuel.2021.121161>
- [16] Anandkumar, G., Nallusamy, S. P., & Sambasivam, R. (2021). Hydrogen induction in a CRDI engine. *Global NEST Journal*. <https://doi.org/10.30955/gnj.06256>
- [17] Karim, G. A. (2003). Hydrogen as a spark ignition engine fuel. *International Journal of Hydrogen Energy*, 28(5), 569–577.
- [18] White, C. M., Steeper, R. R., & Lutz, A. E. (2006). The hydrogen-fueled internal combustion engine. *International Journal of Hydrogen Energy*, 31(10), 1292–1305.
- [19] Das, L. M. (2002). Hydrogen engine: research and development programs in Indian Institute of Technology, Delhi. *International Journal of Hydrogen Energy*, 27(9), 953–965.
- [20] Boretti, A. (2012). Advantages and disadvantages of hydrogen fuelled internal combustion engines. *International Journal of Hydrogen Energy*, 37(12), 9869–9884.
- [21] Verhelst, S., & Wallner, T. (2009). Hydrogen-fueled internal combustion engines. *Progress in Energy and Combustion Science*, 35(6), 490–527.