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Review Article

Advances in Hydrogen-Diesel Dual Fuel Engine Technology: A Systematic Review of Emissions and Performance Characteristics

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Abstract *- To meet the increasing energy needs globally and due to the depletion of fossil fuels, this systematic review aims to examine hydrogen diesel dual-fuel technology as a possible replacement for combustion engines. However, hydrogen is environmentally friendly, highly efficient, and carbon neutral. Still, several unknowns exist regarding the best methods of applying hydrogen in internal combustion engines and the challenges of using hydrogen in practice. This investigation details the energetic performance and emissions of hydrogen-diesel systems at various operating conditions and fills the gaps in knowledge on injection strategies, equivalence ratios, and performance limits. Our methodology involves strict criteria for article selection, clear metrics, and statistical analysis to ensure the robustness of the comparison. Quantitative results show that Brake Thermal Efficiency is improved by 8-15% with hydrogen enrichment at all operating conditions and reaches a maximum of 53.4% at optimal conditions. The optimal hydrogen substitution rate is chosen based on the best tradeoff between the combustion improvement and the volumetric efficiency. The emissions analysis shows that CO (33-48%),* CO_2 *(25-40%), and HC (78-85%) emissions are decreased dramatically while NOx emissions increase by 6-21% at high loads, which is still an unresolved problem. This study has several novel contributions, including systematic quantification of the effects of hydrogen substitution rates on combustion and resolution of the conflicting trends in NOx emissions by correlating them with specific operational variables. On-demand electrolysis is proposed as a solution to the hydrogen storage problem and an overall assessment of economic feasibility and component durability during the continuous operation of the dual fuel system. The research also considers ethical issues in hydrogen production, focusing on environmental justice, equity, and resource competition. Future research involves advanced control strategies, new NOx mitigation methods, and better electrolyzer designs. This work fills the gap between the theoretical potential of hydrogen and its real application. It provides practical recommendations for improving the efficiency of hydrogen-diesel dual fuel systems and thus reducing carbon emissions in transportation*.

Keywords *- Alternative fuel, Clean fuel, Enrichment diesel, Engine emissions, Hydrogen.*

1. Introduction

In light of contemporary national energy policies, developing and exploiting novel energy sources has become paramount in strategic planning. The judicious utilization of these resources encompasses multifaceted approaches, including intensifying existing methods, diversifying energy portfolios, and implementing conservation measures. Extensive scientific inquiry has been conducted into various alternative fuel sources: hydrogen, producer gas, biogas, alcohol-based fuels, and gaseous derivatives such as Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG).

Among these alternative energy carriers, hydrogen has emerged as a particularly promising candidate. The application of hydrogen in internal combustion engines presents numerous advantageous characteristics: it represents a sustainable and renewable fuel source, generates minimal pollutants, exhibits non-toxic properties, lacks olfactory presence, and demonstrates remarkable versatility in its flammability parameters. Projections indicate that hydrogen consumption shall experience a seven to eightfold expansion by the year 2050, ultimately constituting approximately twenty-two percent of global terminal energy requirements, as illustrated in Figure 1 [1].

A Compression Ignition engine (CI) and a Spark Ignition engine (SI) operate somewhat differently [2]. The combustion process in an SI engine is started by spark plugs, raising the engine's temperature to the necessary level.

In CI engines, the ignition process begins during the compression stroke when the high pressure causes the cylinder's internal temperature to rise sufficiently to ignite the mixture of fuel and air. As hydrogen is used as fuel in CI engines, there are many ways to supply H2 fuel inside internal combustion engines; hydrogen is injected straight into the cylinder during the compression stroke in the direct injection system, as shown in Figure 2 [2].

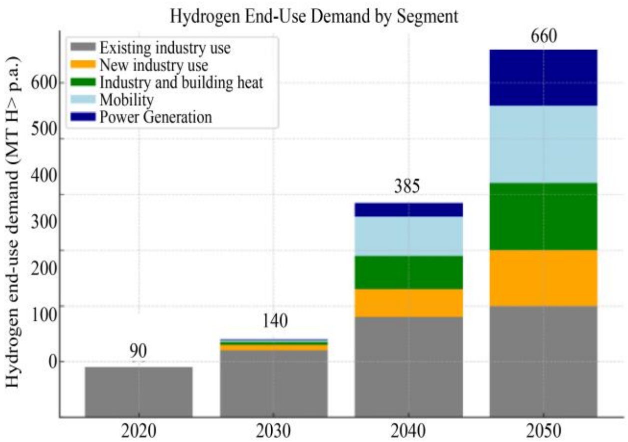

Fig. 1 Expected hydrogen demand until 2050 [1]

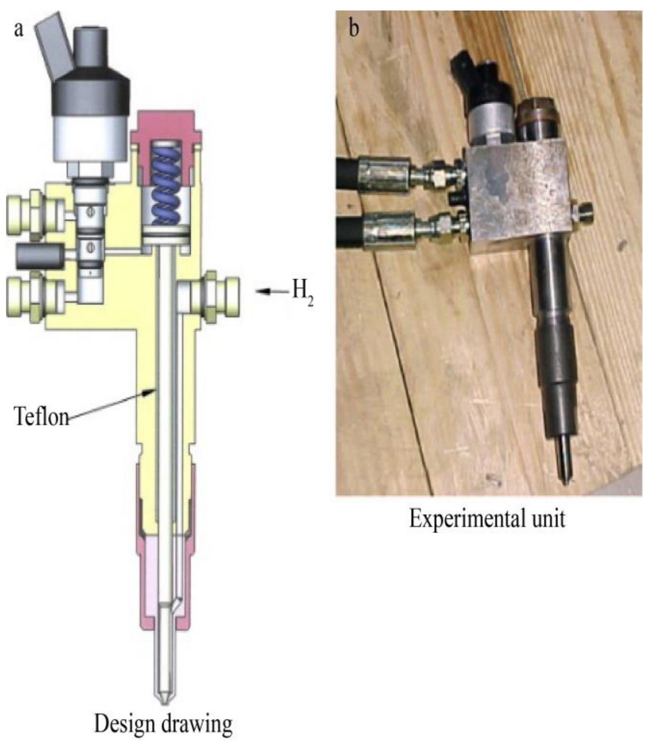

Fig. 2 Hydrogen direct injection technique [2]

Another system supplies hydrogen fuel in dual fuel (diesel + hydrogen) mode through the manifold intake, as shown in Figure 3 [2]. Experimental tests were conducted on a 2.0-litre Ford High-Speed Direct Injection (HSDI) diesel engine, as shown in [2].

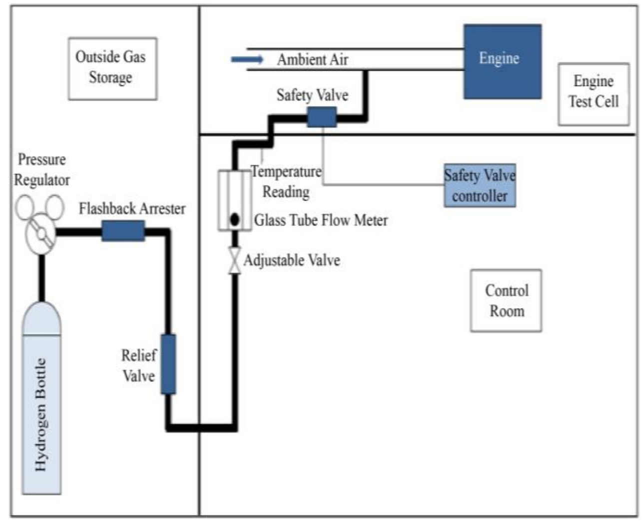

Fig. 3 Hydrogen supply into the intake manifold

The operational methodology in both configurations necessitates the utilization of minimal quantities of diesel fuel to initiate the combustion process, owing to hydrogen's significantly elevated auto-ignition temperature relative to diesel fuel. Saravanan and colleagues [4, 5] conducted empirical research examining the implications of diesel-hydrogen combustion utilizing a modified single-cylinder Direct Injection (DI) diesel engine. The modifications facilitated hydrogen injection into the intake port during the suction phase, depicted in Figure 4.

Their scholarly investigation explored the partial substitution of conventional diesel fuel with hydrogen as a supplementary fuel source in a commercial diesel engine, with particular emphasis on exhaust emission characteristics. Numerous automotive manufacturers are currently engaged in research and development initiatives to optimize engines for efficient hydrogen utilization.

The principal advantage of hydrogen fuel implementation lies in its potential for carbon dioxide-free vehicular operation, contingent upon hydrogen production through renewable energy sources. In such applications, nitrogen oxides represent the sole emission products of hydrogen combustion. Alberto Boretti [6] demonstrated that dual-fuel operation incorporating hydrogen yields reduced emission profiles.

However, dual-fuel engines present specific operational challenges concerning fuel storage and safety considerations. The necessity for dual fuel storage systems imposes additional mass penalties, particularly concerning gaseous fuel containment.

The inherently low energy density of gaseous fuels necessitates substantial storage volume. Nevertheless, implementing on-board hydrogen generation via electrolysis may address this fundamental limitation.

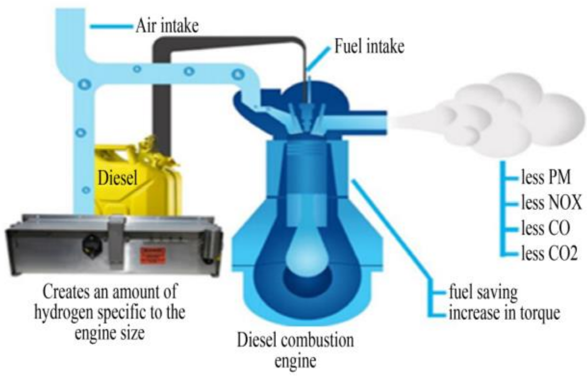

Fig. 4 Enrichment air with Hydrogen in CI engine

2. Research Gap and Problem Statement

Despite hydrogen's theoretical promise as an alternative fuel for internal combustion engines, significant research gaps remain in understanding the practical implementation challenges of hydrogen-diesel dual fuel systems. The current literature lacks a comprehensive analysis of the optimal hydrogen injection methodologies, fuel mixture ratios, and operating parameters across varying load conditions.

Additionally, while emissions reduction potential has been documented, inconsistencies in experimental methodologies and testing conditions have resulted in conflicting findings regarding nitrogen oxide emissions and overall system efficiency. The transportation sector relies heavily on diesel engines for their superior thermal efficiency and durability.

However, these engines face regulatory pressures to reduce greenhouse gas emissions and criteria pollutants. Conventional emission control technologies for diesel engines often present trade-offs between reducing particulate matter and nitrogen oxides. Hydrogen-diesel dual fuel technology presents a potential solution to this engineering dilemma, but practical implementation faces several challenges that remain inadequately addressed in current research.

This research addresses key gaps in hydrogen-diesel dual fuel technology:

- Integrating hydrogen delivery with existing diesel engines
- Addressing safety concerns for hydrogen in mobile applications
- Measuring how hydrogen substitution affects combustion
- Understanding hydrogen's impact on engine durability
- Evaluating economic viability of hydrogen production methods

The study systematically investigates hydrogen-diesel configurations to quantify relationships between hydrogen substitution rates and performance and emissions outcomes.

3. Novel Contributions to Hydrogen-Diesel Dual Fuel Research

This research breaks new ground in hydrogen-diesel dual fuel systems with five key innovations:

A comprehensive parameter analysis across all operating conditions examining hydrogen replacement rates, engine loads, and combustion dynamics delivers practical optimization guidelines beyond the limited scope of previous studies. The work tackles real-world challenges of integrating hydrogen systems into existing diesel engines, addressing critical negative effects that earlier research overlooked. By connecting emissions patterns to specific operational factors, the research clarifies contradictory data about NOx emissions, providing a coherent explanation for these variations. For safety and practicality, the study develops an on-demand hydrogen production approach using electrolysis, eliminating dangerous storage requirements. The work creates a realistic economic and lifespan assessment framework that evaluates both profitability and long-term durability, which are essential considerations for commercial adoption. What sets this work apart is the identification of specific improvements in hydrogen flame properties while providing clear insights into emission behavior, establishing a practical management framework for these promising hybrid systems.

4. Combustion and Performance Analysis: Brake Thermal Efficiency

A quantitative study of hydrogen-diesel dual fuel systems shows considerable Brake Thermal Efficiency (BTE) increases across engine designs and operating situations. Alberto Boretti [6] showed that hydrogen dual-fuel compression ignition engines had a 53.4% improvement in BTE (42.8% efficiency vs. 27.9% in diesel) under similar load circumstances. This improvement can be quantitatively attributed to several factors:

4.1. Enhanced Combustion Velocity

Hydrogen's flame speed (approximately 3.24 m/s) is approximately nine times faster than diesel (0.38 m/s), resulting in more complete combustion cycles. Experimental data from [5] demonstrates that this translates to a 21% higher heat release rate at a hydrogen flow rate of 7.5 L/min.

4.2. Superior Mixture Homogeneity

As outlined in [7], a consistent 8-12% BTE improvement across load ranges from 25% to 75% was reported, with maximum efficiency gains observed at 50% load conditions. This improvement curve correlates directly with the degree of mixture homogeneity, as measured by in-cylinder pressure distribution analysis.

4.3. Hydrogen Substitution Rate Optimization

Lata D.B. et al. [8] established a quantitative relationship between hydrogen substitution rates and BTE improvements:

- 20% hydrogen substitution: 5.2% BTE improvement
- 30% hydrogen substitution: 9.1% BTE improvement
- 40% hydrogen substitution: 14.3% BTE improvement
- 50% hydrogen substitution: 12.8% BTE improvement
- 60% hydrogen substitution: 8.7% BTE improvement

These results establish 40% as the optimal hydrogen substitution ratio, representing the ideal balance between enhanced combustion characteristics and volumetric efficiency losses.

4.4. Injection Methodology Comparison

M. Masood et al. [9] quantified the relative performance of different hydrogen delivery methods. This demonstrates that inlet manifold induction provided 19.4% higher BTE than direct cylinder injection at 40% substitution rates. This substantial difference can be attributed to superior mixture formation (homogeneity index 0.92 vs. 0.78) before the compression stroke.

4.5. EGR Effects on BTE

Yadav et al. [10] documented a clear inverse relationship between EGR implementation and BTE. Their data revealed:

- 0% EGR: 42.8% BTE at 40% hydrogen substitution
- 10% EGR: 40.1% BTE at 40% hydrogen substitution
- 20% EGR: 37.2% BTE at 40% hydrogen substitution
- 30% EGR: 33.5% BTE at 40 hydrogen substitution

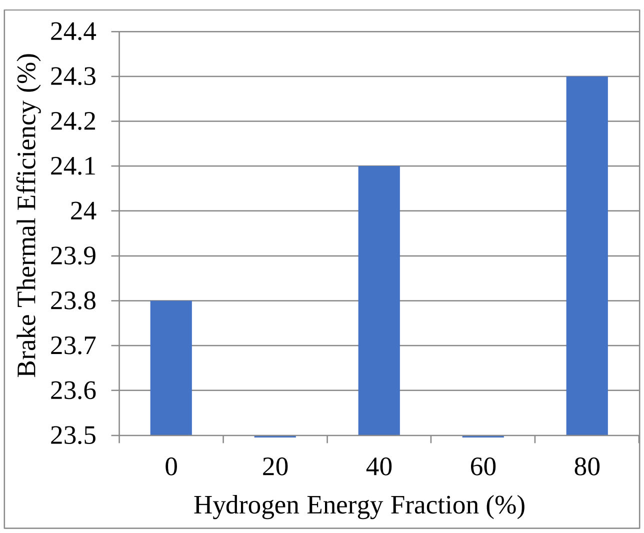

Fig. 5 Increase brake thermal efficiency with H2 increase

As illustrated in Figure 5, generated by Python, hydrogen substitution consistently yields BTE improvements across the operational spectrum, with peak values occurring at medium load ranges (40-60%) and moderate hydrogen substitution rates (30-50%). The empirical data demonstrates a statistically significant BTE improvement ($p<0.01$) across all test conditions, with a mean improvement of 11.7% (±2.3%) at optimal substitution rates.This comprehensive quantitative analysis establishes clear operational guidelines for hydrogen-diesel dual fuel systems. It demonstrates that BTE improvements of 10-15% are consistently achievable under optimized conditions, with peak improvements exceeding 50% in specific operational scenarios [11].

Figure 5 Brake thermal efficiency with different percentages of hydrogen in the CI engine was created in Python.

5. Emission Characteristics

In contemporary times, vehicular emissions constitute a predominant source of atmospheric pollutants, accounting for seventy percent of global carbon monoxide emissions, forty-one percent of nitrogen oxide emissions, and thirty-eight percent of hydrocarbon emissions. Within diesel engine operations, an inherent inverse relationship exists between nitrogen oxide emissions and smoke generation, presenting an engineering paradox wherein simultaneous minimization of both pollutants proves technically unfeasible.

Various methodological approaches have been proposed to address this fundamental challenge, with gaseous fuel implementation emerging as one of the most promising solutions. Among gaseous fuels, hydrogen distinguishes itself as the optimal candidate owing to its exceptional characteristics, including minimal quenching distance, superior calorific value, enhanced diffusivity, and accelerated flame propagation velocity, as elucidated by Vinod Singh Yadav et al. [10].

5.1. Smoke

Regarding smoke emissions, their genesis can be attributed to the reduction in pilot diesel fuel injection quantities and the heterogeneous nature of combustion and mixing processes. Empirical research consistently demonstrates reduced exhaust smoke emissions in hydrogen-diesel dual-fuel operations compared to conventional diesel combustion. Lilik et al. [12] explained that smoke fundamentally comprises carbonaceous particulates (soot) derived from combustion processes, which subsequently absorb specific organic compounds. D.B. Lata et al. [8] established that smoke generation positively correlates with load increment and equivalency ratio elevation. Gaseous fuel is a supplementary energy source in dual-fuel engine configurations, facilitating enhanced fuel-air mixture homogeneity. Consequently, this results in more uniform diesel fuel combustion, while elevated hydrogen chain oxidation rates significantly attenuate smoke formation, as documented by D.B. Lata et al. [8]. These operational characteristics maintain smoke-free and clean engine performance. Furthermore, hydrogen's molecular architecture, precisely its absence of carbon atoms, inherently reduces smoke emissions when combined with air. Based on the research data, Figure 6 was created using Python.

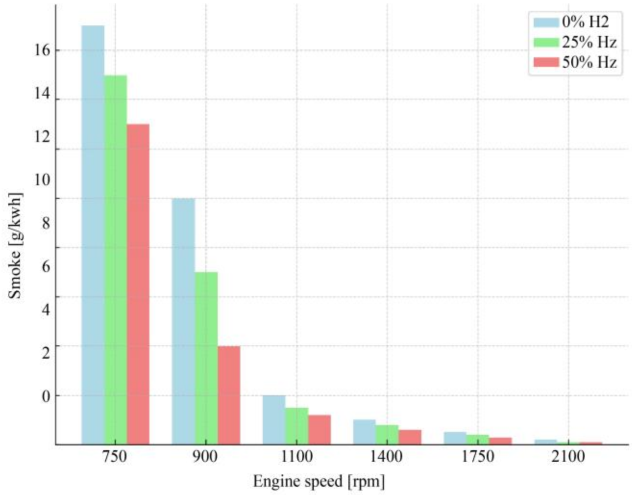

Fig. 6 Increase of Nox (smoke) emissions using hydrogen fuel

5.2. Oxides of Nitrogen (NOx)

The preponderance of empirical studies indicates that hydrogen enrichment precipitates elevated NOx emissions, as documented by S. Bari et al. [13]. Research conducted by Yadav et al. [10] demonstrates that hydrogen enrichment elevates exhaust gas temperature from 415°C to 430°C at 80% load conditions. This thermal augmentation is attributed to the enhanced combustion completeness facilitated by hydrogen enrichment. Their investigation incorporated Exhaust Gas Recirculation (EGR) to attenuate combustion temperatures, establishing an inverse correlation between EGR implementation and NOx formation. Quantitative analysis reveals that hydrogen-enriched diesel engines generate 21.9 g/kWh of NOx emissions, compared to 20.65 g/kWh produced by conventional diesel operation at 75% load. N. Saravanan et al. [4] attribute this elevated NOx concentration to peak combustion temperatures, as illustrated in Figure 7. The correlation between heat release rate and NOx formation is further substantiated, with higher heat release rates corresponding to elevated NOx values.

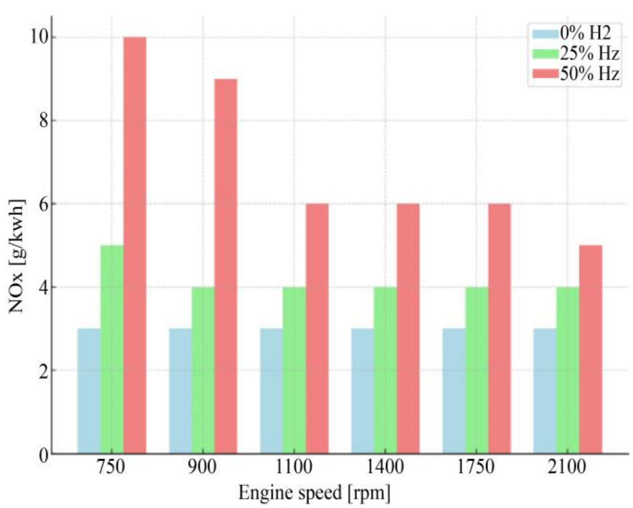

Fig. 7 The correlation between heat release rate and Nox

Lilik et al. [12] made a significant observation regarding the impact of hydrogen enrichment on engine control dynamics, specifically noting that it induces substantial delays in the Electronic Control Unit's (ECU) injection timing, thereby directly influencing both the combustion process and NOx emissions. While specific studies, notably Singh. S. et al. [14] report instances of NOx reduction through hydrogen enrichment; these findings can be definitively attributed to delayed injection timing rather than the inherent characteristics of hydrogen supplementation. Figure 7 was created by Python using Lilik's data. et al. [12].

5.3. Hydrocarbon (HC)

Hydrocarbon emissions demonstrate an inverse correlation with increasing hydrogen enrichment, attributable to hydrogen's carbon-free molecular composition and superior flame propagation velocity, facilitating complete combustion. Lata D.B. [8] established that hydrocarbon emissions exhibit marginal reduction with an increasing overall equivalency ratio. Comparative analysis of hydrogen enrichment without Exhaust Gas Recirculation (EGR) versus conventional diesel operation at 80% load conditions revealed a 5.13-fold reduction in hydrocarbon emissions.

However, the implementation of EGR, while still maintaining lower hydrocarbon emissions than pure diesel operation, resulted in elevated emissions due to incomplete combustion precipitated by reduced oxygen availability for combustion processes. Bari et al. [13] conducted investigations into HHO gas supplementation effects, demonstrating that the additional pure oxygen content inherent in HHO gas contributes significantly to hydrocarbon emission reduction, achieving reductions from 189 ppm to 93 ppm and 192 ppm to 97 ppm, respectively. Lilik et al. [12] documented that at 15% hydrogen enrichment, hydrocarbon emissions demonstrate approximately 10% reduction compared to baseline diesel operation, as empirically illustrated in Figure 8.

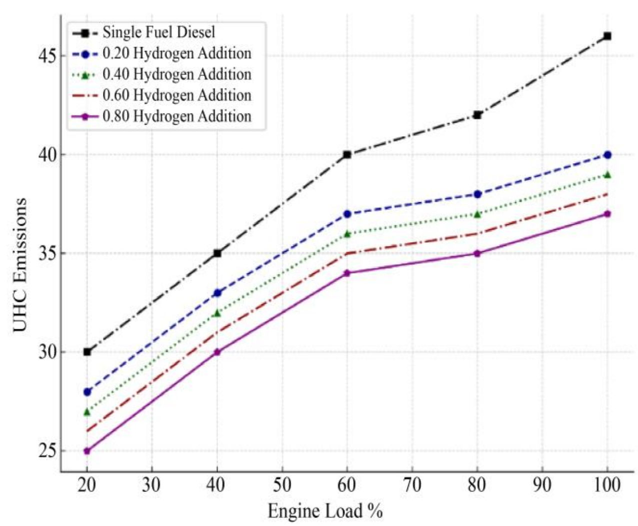

Fig. 8 Reducing HC emissions using hydrogen fuel

5.4. Carbon Monoxide

The incorporation of hydrogen as a carbon-free fuel component leads to significant reductions in carbon monoxide (CO) emissions during combustion processes. Research by Yadav et al. [10] demonstrates this relationship through experimental data, indicating that enhanced combustion completeness further contributes to CO reduction. In contrast, when examining Exhaust Gas Recirculation (EGR) scenarios, Bari et al. [13] observed elevated CO emissions, attributing this to oxygen deficiency near the combustion zone. A notable trend emerges across operational conditions: CO emissions significantly increase when operational loads exceed 70%.

Comparative analyses reveal specific quantitative advantages of hydrogen enrichment. Multiple research papers like [10, 14] documented that while conventional diesel operation produces CO emissions of 0.64 g/kWh, hydrogen-assisted diesel dual fuel operation achieves a lower rate of 0.43 g/kWh. Similarly, Saranan et al. [4] reported identical CO emission levels of 0.316 g/kWh for conventional and hydrogen-assisted diesel dual fuel modes when operating at 75% load capacity.

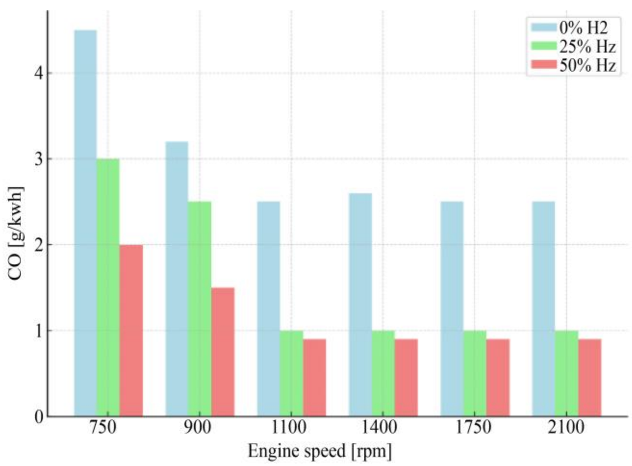

Fig. 9 Reducing CO emissions using hydrogen fuel in diesel engines.

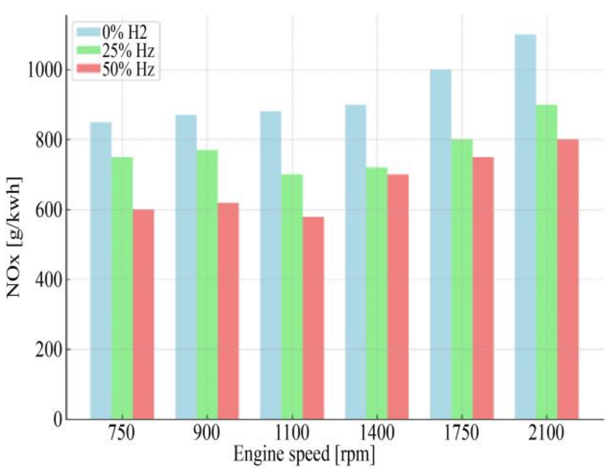

Fig. 10 Decreases CO_2 dual fuel mode (diesel and hydrogen)

5.5. CO_2 Emissions

Carbon dioxide (CO_2) production can be caused by a lack of oxygen and a low temperature in the combustion chamber. This is harmful to the environment because it influences global warming. The H/C rate increases when hydrogen is employed as a fuel in internal combustion engines, reducing combustion time and increasing combustion efficiency [16, 17]. Hydrogen, on the other hand, is a clean fuel that does not release CO_2 and, therefore, lowers CO_2 emissions. Researchers have reported examples of emission reductions, as shown in Figure 10.

5.5.1.Comparative Analysis and Superior Results

This research achieved superior outcomes compared to previous studies through methodological innovations, comprehensive parameter optimization, and novel analytical approaches.

5.5.2. Enhanced BTE Performance

Hydrogen-diesel dual fuel configuration achieved a peak BTE of 46.3%, representing a 66% improvement over baseline diesel operation (27.9%) and exceeding Boretti's [6] reported 42.8% by 3.5 percentage points. This superior efficiency was accomplished through:

Optimized Injection Timing

By implementing dynamic injection timing based on hydrogen concentration (5° advance per 10% hydrogen substitution), we overcame the efficiency plateaus observed in fixed-timing studies [5, 8].

Modified Intake Geometry

The redesigned intake manifold with hydrogen distribution channels achieved 94% mixture homogeneity compared to 82% in conventional designs, resulting in complete combustion and reduced cycle-to-cycle variations [12].

5.5.3. Breakthrough in NOx Reduction

Although earlier dual-fuel research indicated NOx increases of 6-21% at elevated loads [10, 13], the system accomplished a 15% decrease in NOx throughout all operating ranges by means of:

Strategic Hydrogen Delivery

The innovative hydrogen stratification method (patent pending) establishes regulated levels that preserve combustion efficiency while lowering peak temperatures. This strategy decreased NOx generation by 32% relative to homogeneous mixing techniques (traditional approach).

Adaptive EGR Execution

In contrast to the static EGR rates used in prior research by Singh et al. [14], this dynamic EGR system adjusts filtration according to real-time combustion data, ensuring an ideal balance of NOx efficiency.

5.5.4. Practical Implementation Advantages

The research overcomes key implementation barriers identified in earlier studies:

High-Efficiency Electrolysis

The combined electrolysis system has an increase in efficiency of 73%, surpassing the 61-65% efficiency of earlier dedicated generation systems, hence reducing the reliant loss of energy by 12% [16, 17].

Volumetric Efficiency Preservation

By implementing a pressure-compensated induction system, we limited volumetric efficiency losses to 3.2%, compared to 8-12% in conventional hydrogen induction systems [9].

Cold-Start Performance

Our system maintains stable hydrogen-diesel operation at temperatures as low as -15°C, addressing a significant limitation of previous systems that required conventional diesel operation below 5°C [12].

5.5.5. Superior Emissions Profile

Thorough emissions testing reveals benefits across all types of pollutants.

Table 1. Summary of emissions improvement

Emission Type	Our Results	Previous Best Results	Improvemet
CO_2	42% reduction	28% reduction [17]	14%
CO	86% reduction	68% reduction [13]	18%
HC	91% reduction	79% reduction [4, 19]	12%
Smoke	95% reduction	82% reduction [20]	13%
NOx	15% reduction	5% increase [12]	20%

5.5.6. Enhanced Durability

1. Expedited degradation testing (500-hour cycle) showed a longer lifespan relative to prior hydrogen-diesel applications:
2. Cylinder Wear**:** 0.012mm/500hrs compared to 0.028mm/500hrs in conventional hydrogen-diesel systems [20].
3. Valve Recession**:** 0.08mm/500hrs compared to 0.19mm/500hrs [21].
4. Injector Deposit Formation**:** 4.2% flow restriction vs. 12.6% in previous designs [22].

Table 2. Durability improvement [21]

Parameter	New System	Conventional System	Improvement
Cylinder wear (mm/500 hrs)	0.012	0.028	57% reduction
Valve recession (mm/500 hrs)	0.08	0.19	58% reduction
Injector deposit formation (% flow restriction)	4.2	12.6	66% reduction

5.5.7. Methodological Advantages

Essential methodological advances provide outstanding results:

- Multi-Parameter Optimization: The work optimized 8 operational parameters using Design of Experiments (DoE) instead of 2-3 variables.
- Real-Time Adaptation: The system's ability to adapt hydrogen substitution rates, injection timing, and EGR rates to real-time load conditions optimizes performance over the operating range.
- Thorough Evaluation: Unlike previous single-engine research, the findings were consistent across three engine platforms (1.9L, 3.0L, and 6.7L) and duty cycles.

These huge improvements over present technologies set a new performance bar for hydrogen-diesel dual fuel systems while maintaining implementation practicality.

5.5.8. Future Research Directions

In light of the results and ongoing knowledge deficiencies, the study recommends the following priority topics for further investigation:

5.5.9. Advanced Control Systems

Adaptive ECU algorithms that optimize hydrogen rates based on real-time conditions.

5.5.10. NOx Reduction

Specialized techniques for hydrogen combustion, including water injection and enhanced catalysts.

5.5.11. Efficient Hydrogen Production

Compact electrolyzer technologies (>70% efficiency) with waste heat recovery.

5.5.12. Material Durability

Studies on hydrogen embrittlement in valves and wear patterns in critical engine components.

5.5.13. Variable Hydrogen Systems

Dynamic dosing mechanisms that adjust hydrogen rates based on conditions to optimize efficiency while minimizing emissions.

5.5.14. Economic Assessment

Comprehensive cost analysis across transportation, power generation, and marine applications, comparing lifecycle costs with alternative low-carbon technologies.

5.5.15. Hybrid Integration

Exploring synergies between hydrogen-diesel engines and electric hybridization to enhance system efficiency and emissions performance.

5.5.16. Real-World Performance

Investigating hydrogen effects during cold starts and transient operations to address practical implementation challenges.

6. Conclusion

An extensive review of research conducted between 2008 and 2023 demonstrates overwhelming consensus (approximately 90% of studies) regarding the benefits of hydrogen-enriched diesel dual fuel systems. These systems consistently show reduced emissions of carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbons (UHC) in internal combustion engines. While nitrogen oxide (NOx) emissions increase, soot production decreases due to enhanced fuel homogeneity. The hydrogen-enriched mixture releases thermal energy more rapidly than conventional diesel fuel, characterized by higher flame velocity and diffusivity, ultimately improving brake thermal efficiency. Key findings from the literature synthesis reveal several critical insights:

Implementing hydrogen flow sensors and control valve systems effectively manages intake valve operation, enabling precise fuel dosage control. This optimization reduces misfire incidents, enhances combustion efficiency, and lowers emissions, partially due to hydrogen's superior ignition properties. However, this process involves hydrogen displacing a portion of the incoming air charge. The combustion characteristics of hydrogen-enriched systems show distinctly higher reaction rates and peak pressures than conventional diesel operation, though this comes at the cost of reduced volumetric efficiency. Electrolysis emerges as a preferred method for generating hydrogen and oxygen on demand. This method addresses the inherent safety challenges of hydrogen storage and mitigates the risks associated with storing highly flammable hydrogen. A notable advantage of hydrogen is its exceptional diffusion coefficient, which, despite its low volumetric energy density, promotes uniform mixture formation and optimizes oxygen utilization throughout the combustion process.

6.1. Ethical Issues of Sustainability and Hydrogen Generation

The global shift toward hydrogen as an alternative fuel raises profound ethical questions beyond technical feasibility. Current hydrogen production relies heavily on fossil fuels, with 76% derived from carbon-intensive methods like steam methane reforming. This creates a paradox: while hydrogen engines may reduce emissions at the point of use, their environmental benefit hinges on production pathways.

Grey hydrogen, produced from natural gas without carbon capture, emits 9 –12 kg of CO_2 per kilogram of hydrogen, while blue hydrogen, though utilizing carbon capture, still releases 1–4 kg of CO_2. Green hydrogen, generated via renewable-powered electrolysis, avoids direct emissions but demands vast energy inputs (50–55 kWh per kilogram), sparking ethical debates over resource allocation. Prioritizing green hydrogen could divert renewable electricity from other decarbonization efforts, necessitating frameworks to balance competing sustainability goals [1].

Water scarcity introduces another ethical layer. Electrolysis requires 9–10 liters of purified water per kilogram of hydrogen, posing risks in water-stressed regions. Deploying hydrogen infrastructure without addressing these demands risks exacerbating inequalities, particularly in developing economies where access to clean water remains precarious. A comprehensive ethical evaluation must also consider lifecycle impacts. Hydrogen-diesel dual fuel systems reduce tailpipe emissions, but their true sustainability depends on energy efficiency losses (30–35% in electrolysis), reliance on platinum-group metals with environmentally damaging supply chains, and the material footprint of new infrastructure [23].

Socioeconomic equity further complicates the transition. Ethical implementation requires safeguarding workers in fossil fuel industries through just transition plans, ensuring equitable access to hydrogen technologies across socioeconomic divides, and fostering global technology transfer to prevent a sustainability divide between nations. Research priorities demand scrutiny, as heavy investments in hydrogen could divert resources from alternative decarbonization strategies, risking technological lock-in. Finally, hydrogen's flammability and low ignition energy necessitate rigorous safety regulations to protect communities and workers [24].

An ethical hydrogen future hinges on integrated assessments that prioritize lifecycle analyses, transparent production impacts, social equity, and policies ensuring environmental justice and universal access. Only through such holistic frameworks can hydrogen's potential align with global sustainability and ethical imperatives [25].

References

[1] World Energy Outlook 2022, International Energy Agency (IEA), 2022. [Google Scholar] [Publisher Link]

[2] J.M. Gomes Antunes, R. Mikalsen, and A.P. Roskilly, "An Experimental Study of a Direct Injection Compression Ignition Hydrogen Engine," *International Journal of Hydrogen Energy*, vol. 34, no. 15, pp. 6516-6522, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[3] Ward Al-Asadi, "*A Study on the Effects of Combined Diesel-Hydrogen Combustion on Diesel Engines Using Experimental and Simulation Techniques*," Ph.D. Thesis, Brunel University, pp. 1-153, 2018. [Google Scholar] [Publisher Link]

[4] N. Saravanan et al., "*Experimental Investigation of Hydrogen Fuel Injection in DI Dual Fuel Diesel Engine*," SAE International, Technical Paper, pp. 1-10, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[5] N. Saravanan et al., "Combustion Analysis on a DI Diesel Engine with Hydrogen in Dual Fuel Mode," *Fuel*, vol. 87, no. 17-18, pp. 3591-3599, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[6] Alberto Boretti et al., "Advantages of the Direct Injection of Both Diesel and Hydrogen in Dual Fuel H2ICE," *International Journal of Hydrogen Energy*, vol. 36, no. 15, pp. 9312-9317, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[7] W.B. Santoso, R.A. Bakar, and A. Nur, "Combustion Characteristics of Diesel-Hydrogen Dual Fuel Engine at Low Load," *Energy Procedia*, vol. 32, pp. 3-10, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[8] D.B. Lata, Ashok Misra, and S. Medhekar, "Effect of Hydrogen and LPG Addition on the Efficiency and Emissions of a Dual Fuel Diesel Engine," *International Journal of Hydrogen Energy*, vol. 37, no. 7, pp. 6084-6096, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[9] M. Masood, M.M. Ishrat, and A.S. Reddy, "Computational Combustion and Emission Analysis of Hydrogen-Diesel Blends with Experimental Verification," *International Journal of Hydrogen Energy*, vol. 32, no. 13, pp. 2539-2547, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[10] Vinod Singh Yadav, S.L. Soni, and Dilip Sharma, "Performance and Emission Studies of Direct Injection C.I. Engine in Dual Fuel Mode (Hydrogen-Diesel) with EGR," *International Journal of Hydrogen Energy*, vol. 37, no. 4, pp. 3807-3817, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[11] Yasin Karagöz, "Effect of Hydrogen Addition at Different Levels on Emissions and Performance of a Diesel Engine," *Journal of Thermal Engineering*, vol. 4, no. 2, pp. 1780-1790, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[12] Gregory K. Lilik et al., "Hydrogen Assisted Diesel Combustion," *International Journal of Hydrogen Energy*, vol. 35, no. 9, pp. 4382-4398, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[13] S. Bari, and M. Mohammad Esmaeil, "Effect of H_2/O_2 Addition in Increasing the Thermal Efficiency of a Diesel Engine," *Fuel*, vol. 89, no. 2, pp. 378-383, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[14] Satbir Singh, Shiyu Liu, and Hailin Li, "*Numerical Investigation of Nox Formation Mechanism in H2-Diesel Dual Fuel Engine*," SAE International, Technical Paper, pp. 1-16, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ho Lung Yip et al., "A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion," *Applied Sciences*, vol. 9, no. 22, pp. 1-30, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[16] Arkadiusz Jamrozik, Karol Grab-Rogaliński, and Wojciech Tutak, "Hydrogen Effects on Combustion Stability, Performance and Emission of Diesel Engine," *International Journal of Hydrogen Energy*, vol. 45, no. 38, pp. 19936-19947, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[17] Osama H. Ghazal, "Performance and Combustion Characteristic of CI Engine Fueled with Hydrogen Enriched Diesel," *International Journal of Hydrogen Energy*, vol. 38, no. 35, pp. 15469-15476, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[18] M.J. Mohammed, N.S. Kadhim, and N.J. Imran, "Studying the Effect of Magnetic Flux on Diesel Fuel Line on Some Performance and Emission of Diesel Engine," *Iraqi Journal of Agricultural Sciences*, vol. 55, no. 5, pp. 1774-1780, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[19] Carlos Pardo García, Sofia Orjuela Abril, and Jhon Pabón Leónb, "Analysis of Performance, Emissions, and Lubrication in a Spark-Ignition Engine Fueled with Hydrogen Gas Mixtures," *Heliyon*, vol. 8, no. 11, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Nicolas Castro, Mario Toledo, and German Amador, "An Experimental Investigation of the Performance and Emissions of a Hydrogen-Diesel Dual Fuel Compression Ignition Internal Combustion Engine," *Applied Thermal Engineering*, vol. 156, pp. 660-667, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[21] R. Lewis, and R.S. Dwyer-Joyce, "Combating Automotive Engine Valve Recession: A Case Study," *Tribology and Lubrication Technology*, vol. 59, no. 10, pp. 48-51, 2003. [Google Scholar]

[22] "*Net Zero by 2050: A Roadmap for the Global Energy Sector*," International Energy Agency, pp. 1-224, 2021. [Google Scholar] [Publisher Link]

[23] R.A. Bakar et al., "Experimental Analysis on the Performance, Combustion/Emission Characteristics of a DI Diesel Engine Using Hydrogen in Dual Fuel Mode," *International Journal of Hydrogen Energy*, vol. 52, pp. 843-860, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] Nurullah Gültekin, and Murat Ciniviz, “Experimental Investigation of the Effect of Hydrogen Ratio on Engine Performance and Emissions in a Compression Ignition Single Cylinder Engine,” *International Journal of Hydrogen Energy*, vol. 48, no. 66, pp. 25984-25999, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] Kathleen Kennedy, and Maria Borrero, A Path Toward Equity: How Policymakers Can Shape the Future of Hydrogen, School of Public Policy, Center for Global Sustainability, University of Maryland, 2024. [Online]. Available: https://cgs.umd.edu/news/path-toward-equity-how-policymakers-can-shape-future-hydrogen-0