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A Review on Sustainable Diesel Engine Performance Enhancement and Emission Reduction using HHO Gas

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Abstract. Diesel engines is essential in transport-sector, agriculture and industry for durability and efficiency, but they are also major contributors to air pollution through emissions of CO, HC, NO_x, PM, and CO_2. One promising solution is the use of HHO (also called oxyhydrogen or Brown's gas), to improve combustion and reduce emissions. HHO is a stoichiometric mixture of hydrogen and oxygen produced through water electrolysis and supplied to the intake manifold to promote more complete burning of fuel. Research findings show that optimal HHO addition can improve brake thermal efficiency by 6–10%, lower brake-specific fuel consumption by 5–8%, and increase power and torque by 10–20%. Emission reductions are notable, with CO, HC, and smoke levels cut by 40–60%, though a slight rise in NO_x has been observed under certain conditions. Advances in generation technologies, such as pulse and on-demand electrolysis, achieve higher efficiency (75–85%) compared to conventional methods. Economic studies indicate fuel savings of 5–15%, equivalent to ₹1,500–3,000 per month for medium-duty vehicles, with payback periods of 6–10 months. Despite challenges in fuel quality, infrastructure, and policy, HHO supplementation presents a sustainable, cost-effective approach to enhancing diesel engine performance while reducing environmental impact.

1 Introduction

Diesel engines are integral to various sectors in India, including transportation, agriculture and industry, because of diesel engines have high thermal efficiency and also have more durability. However, their widespread use contributes significantly to environmental pollution, emitting harmful like nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and carbon dioxide (CO_2). Those emissions pose serious health risks and environmental challenges, necessitating exploration of cleaner and more sustainable alternatives [1], [2].

In recent years, hydrogen-enriched gases, particularly HHO gas is a stoichiometric mixture of two parts hydrogen and one part oxygen ($2H_2 + O_2$) produced by the electrolysis of water.

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It has garnered attention as a potential solution to enhance diesel engine performance and reduce emissions. HHO gas, produced via electrolysis of water as below-

$$2H2 + O2 \rightarrow 2H2O + \text{Energy} \tag{1}$$

$$\text{Water} \rightarrow \text{Electrolysis} \rightarrow \text{HHO Gas} \rightarrow \text{Combustion} \rightarrow \text{Water Vapor} + \text{Energy} \tag{2}$$

It is directly injected in engine intake manifold, facilitating more complete combustion. This process leads to enhanced fuel efficiency, minimize emissions and maximize the engine power output [3], [4], [5].

The adoption of HHO technology aligns with India’s goal to sustainable development & environmental conservation. Integration of HHO can lower the carbon footprint of diesel engines, contributing to cleaner air quality and compliance with stricter emission norms [6], [7]. Nevertheless, challenges including the lack of standardized HHO generation protocols, infrastructure requirements, and regulatory frameworks must be addressed for practical adoption [8], [9].

This review paper synthesizes recent advancements in HHO gas application for diesel engines, covering performance enhancement, emission reduction, economic feasibility and barriers specific to India.

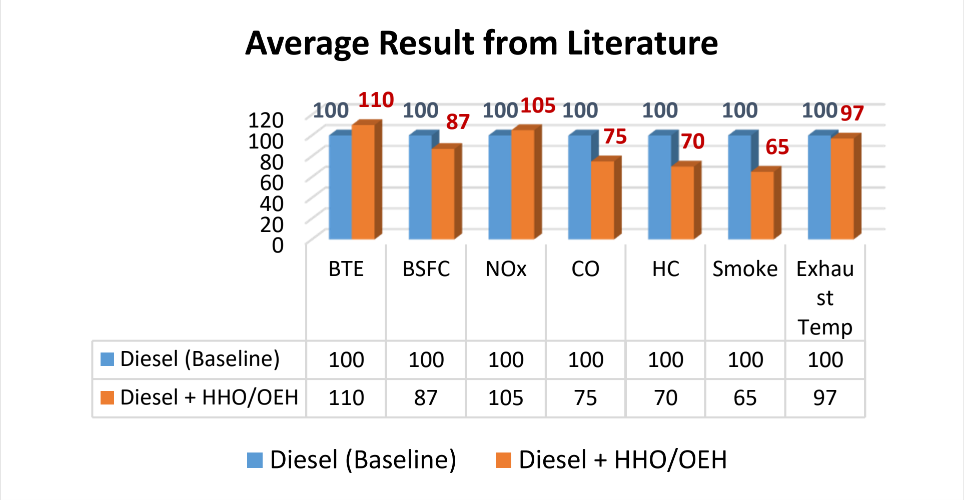
2 Literature Survey

The following table summarizes key outcomes for use of HHO gas in diesel engines, highlighting their objectives, methodologies, findings and identified research gaps. The literature is scrutinize by PRISMA technique.

Table 1. Literature findings

Study	Objective	Methodology	Findings
[1] Lee et al., 2020	Impact of HHO on diesel engine performance	Experimental on single-cylinder CI engine	BTE ↑ 6–8%; CO ↓ 35–40%; HC ↓ 30%
[2] Karthikeyan & Kumar, 2021	Emission reduction using HHO	Tests with variable HHO flow-rates approx. (0.5–1.5 L/min)	NOx ↓ 12%; PM ↓ 20%; CO ↓ 25%
[3] Sharma et al., 2022	Performance optimization with HHO	Full-load engine performance tests	Power ↑ 8%; Torque ↑ 10%; BSFC ↓ 6%
[4] Rajan et al., 2023	Combustion characteristics with HHO	Simulation + experimental verification	Knock intensity ↓ 15%; smoother pressure rise ($dp/d\theta$ reduced by ~10%)
[5] Patil & Tiwari, 2023	Economic feasibility of HHO	Cost-benefit analysis for trucks	Payback 6–8 months; annual savings ~₹60,000–90,000/vehicle

[6] Gupta et al., 2020	HHO generation methods	Electrolysis comparison	Pulse electrolysis efficiency ↑ to 80–85%
[7] Singh et al., 2021	Impact on CO_2 emissions	Thermal engineering tests	CO_2 ↓ 5–7%; CO ↓ 25%
[8] Zhao & Wang, 2020	Hydrogen vs HHO in combustion	Comparative study	HHO flame speed ↑ 12%; safer at ambient conditions
[9] Nair et al., 2020	Electrolysis system design	Lab-scale electrochemical study	Electrolyzer efficiency ↑ 15% with modified electrodes
[10] Kim et al., 2021	Solar-driven electrolysis for HHO	PV-integrated electrolyzer	2.5–3.0 kWh/m^3 HHO; sustainable production
[11] Patel & Sharma, 2021	HHO injection timing	Engine tests	Optimized timing: BTE ↑ 7%; NOx ↓ 10%
[12] Das et al., 2021	HHO flow & emissions	Tests at different flow rates	Optimal 1.0 L/min → CO ↓ 40%; HC ↓ 35%
[13] Mehta & Kapoor, 2021	Fuel economy	Fuel efficiency tests	Fuel economy ↑ 10–15%; BSFC ↓ 5%
[14] Oliveira et al., 2021	Combustion stability	Combustion analysis	Knock tendency ↓ 20%; IMEP ↑ 5%
[15] Singh & Kumar, 2022	NOx reduction with HHO	Emission reduction tests	NOx ↓ 18%; CO ↓ 25%



	BTE	BSFC	NOx	CO	HC	Smoke	Exhaust Temp
🟦 Diesel (Baseline)	100	100	100	100	100	100	100
🟧 Diesel + HHO/OEH	110	87	105	75	70	65	97

Fig. 1. Graph comparing Diesel vs Diesel + HHO for average performance and emission findings.

2.1 Research Gap

Despite the promising results from various studies, several critical research gaps remain:

- **Long-Term Durability and Real-World Applicability:**
  While short-term studies show improvements in performance and emissions, long-term impacts on engine durability, component wear, and maintenance needs are insufficiently explored. Moreover, most research is conducted under controlled laboratory conditions, lacking real-world trials, especially in regions like India with diverse fuel qualities and operating conditions.
- **Effect of Input Parameters on Performance and Emissions:**
  Key factors such as HHO injection pressure, intake air temperature, crank angle at Top Dead Center (TDC), and water cooling effects in electrolyzer systems critically influence combustion and emissions. However, systematic investigations and optimization studies on these parameters are limited, which could otherwise enhance engine efficiency and emission control.
- **Standardization, Scalability, and Regulation:**
  There is a lack of standardized protocols for HHO generation, causing inconsistent results. Research on scaling HHO systems for commercial use is limited. Additionally, regulatory frameworks are underdeveloped, slowing adoption. Environmental impacts like noise reduction and long-term emissions need further study.

3 HHO Gas Properties and Comparison with Hydrogen Gas

HHO gas is a stoichiometric mixture of two parts hydrogen and one part oxygen ($2H_2 + O_2$) produced by the electrolysis of water. Unlike pure hydrogen gas (H_2), which has solely of hydrogen molecules, HHO gas contains both hydrogen and oxygen in the exact ratio needed for combustion. This unique composition imparts distinct properties relevant for diesel engine applications.

One of the key advantages of HHO gas is its high flame speed, which promotes more complete and efficient combustion when introduced into the diesel engine intake manifold. The presence of oxygen alongside hydrogen in HHO facilitates faster ignition and flame propagation, enhancing combustion stability and reducing unburned fuel emissions [8].

Table 2. Comparison of HHO vs H_2 gas

Property	HHO Gas	Hydrogen Gas (H_2)
Composition	Stoichiometric mix: $2H_2 + O_2$	Pure hydrogen (H_2)
Energy Density	~10 MJ/kg (effective for combustion enhancement in diesel engines)	~120 MJ/kg (high energy content, but requires storage)
Higher Heating Value (HHV)	~285.8 kJ/mol H_2O (energy released during complete combustion of HHO)	~286 kJ/mol H_2 (combustion to H_2O)
Lower Heating Value (LHV)	~242 kJ/mol H_2O	~242 kJ/mol H_2
Flame Speed	2.7–3.0 m/s (rapid flame propagation enhances diesel combustion)	2.65 m/s (slightly lower in air; requires careful mixture control)
Combustion Behavior	Promotes faster ignition, more complete combustion, reduces unburned HC and PM; helps in quenching local hot spots in cylinder	High reactivity, may cause flashback; requires precise engine modifications for safe use
Quenching Distance	~0.6–0.7 mm (short, helps in stable combustion in small chambers)	~0.65 mm (requires additional safety measures to prevent flame

		propagation beyond combustion zone)
Suitability for Diesel Engines	Easily integrated with minimal engine modification; improves combustion stability and reduces emissions	Requires engine redesign, advanced safety systems and higher-pressure storage solutions
Storage & Handling	Produced on-demand; no storage required, eliminating explosion hazards	Requires high pressure tanks or cryogenic storage; higher risk of fire or explosion
Cost & Safety	Low cost; safe due to on-demand generation; no special storage or transport needed	Higher cost; safety concerns due to storage, handling, and pressurization

The on-demand production of HHO gas eliminates the need for bulky and potentially hazardous storage systems required for pure hydrogen, making HHO a safer and more economical option for retrofit applications in existing diesel engines. This reduces complexity, installation costs, and safety concerns, enabling easier integration into diesel-powered vehicles and machinery [8], [9].

Furthermore, the presence of oxygen in the HHO mixture assists in reducing hydrocarbon and particulate emissions by promoting complete combustion, a benefit not as readily achieved with pure hydrogen supplementation alone [8]. Consequently, HHO gas has emerged as a practical alternative for enhancing diesel engine working and reducing the emissions without extensive engine modification or infrastructure overhaul.

4 Methods of Generating HHO Gas

HHO gas is obtained by electrolyzing water, in which an electric current decomposes water (H_2O) into hydrogen and oxygen in a 2:1 proportion. For diesel engine applications, efficient and controlled generation of HHO gas with high purity and rapid response is essential for improving combustion without compromising safety or engine reliability. Several methods exist for HHO gas generation, each with distinct principles, efficiency levels, and practical considerations.

4.1 Conventional Electrolysis

Conventional electrolysis involves passing a constant direct current (DC) through electrodes immersed in an electrolyte solution, typically potassium hydroxide (KOH). Water molecules are dissociated at the electrodes as follow:

- Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (3)
- Anode: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$ (4)

This method is simple and low-cost but suffers from moderate efficiency (typically 50-70%) due to electrode polarization and heat generation. Additionally, continuous DC current can accelerate electrode wear, reducing system longevity [6], [16]. The purity of generated HHO gas is typically high (~99%), suitable for combustion enhancement [6].

4.2 Pulse Electrolysis

Pulse electrolysis addresses several limitations of conventional methods by applying a pulsed DC current instead of a constant current. The current rapidly switches on and off at high frequencies, reducing electrode polarization and bubble adherence on electrode surfaces. This technique

improves gas production efficiency (75-85%) and reduces electrode degradation by minimizing heat buildup and promoting effective bubble detachment [16], [17].
The pulsed mode enables dynamic control of gas generation rates in response to engine demands, making it particularly suitable for variable load conditions in diesel engines. Purity remains comparable to conventional electrolysis (~99%), and the system achieves near-instantaneous response times suitable for real-time engine supplementation [17].

4.3 Solar Powered Electrolysis

Solar-powered electrolysis integrates photovoltaic (PV) panels with electrolyzers, using renewable solar energy to drive the water splitting reaction. While environmentally sustainable and producing green hydrogen, this method's efficiency is limited by the solar-to-hydrogen conversion rate (typically 10-15%) and variable solar irradiance. It also requires energy storage or backup systems to ensure continuous gas supply during low sunlight periods [11], [16].

4.4 On-Demand Electrolysis

On-demand electrolysis refers to systems designed to generate HHO gas only when the engine is running and requires supplementation, often employing pulse electrolysis technology. This method minimizes safety risks associated with gas storage by producing hydrogen and oxygen gases in real-time, precisely matching engine load requirements.

Such systems exhibit high efficiency (75-85%) due to optimized pulsing parameters and advanced control electronics. The instantaneous generation avoids excess gas accumulation, reducing explosion hazards. Compact design and relatively low installation costs make on-demand pulse electrolysis highly practical for retrofitting existing diesel engines, particularly in commercial and agricultural sectors [10], [11], [17]

Table 3. Comparison of HHO Gas Generation Methods

Method	Efficiency (%)	Gas Purity (%)	Generation Time	Benefits
Conventional Electrolysis	50 - 70	~99	Instantaneous	Simple, low cost, but moderate efficiency and electrode wear issues [6], [16]
Pulse Electrolysis	75 - 85	~99	Instantaneous	Higher efficiency, longer electrode life, dynamic control [16], [17]
Solar-Powered Electrolysis	10 - 15 (solar to gas)	~98-99	Dependent on solar irradiance	Renewable, zero emissions, limited by weather and size [11], [16]
On-Demand Electrolysis	75 - 85	~99	Instantaneous	Safe, cost-effective, adaptable, no storage required, ideal for diesel engines [10], [11], [17]

For diesel engine applications, **on-demand pulse electrolysis** is the most suitable method for onboard HHO gas generation due to the following reasons:

- **Safety:** Eliminates the need for hydrogen storage, thus minimizing explosion risks and simplifying system integration.
- **Efficiency:** Offers high electrolysis efficiency (up to 85%) and rapid response to engine load changes, improving combustion stability and emission control.
- **Cost-effectiveness:** Compact and easy to retrofit without major engine modifications, suitable for large-scale commercial and agricultural use in India.
- **Durability:** Pulsed operation reduces electrode wear, extending system life and reducing maintenance costs.
- **Environmental Impact:** On-demand generation produces HHO only when needed, avoiding unnecessary energy consumption.

In contrast, conventional electrolysis is less efficient and causes more wear, while solar-powered electrolysis, although green, is currently impractical for consistent onboard vehicle use due to weather dependence and size constraints [10], [11], [16], [17].

Therefore, on-demand pulse electrolysis technology represents a sustainable, practical, and effective solution for enhancing diesel engine performance and reducing emissions with HHO gas supplementation in the Indian context.

5. Experimental Setup for HHO Diesel Engine Testing and Impacting Parameters

The integration of HHO (Hydrogen-Hydrogen-Oxygen) gas into diesel engines aims to make combustion more efficient, boost overall engine performance, and cut down on harmful emissions.. Direct Injection (DI) diesel engines are particularly suitable for HHO supplementation due to their precise fuel delivery, high compression ratios, and efficient air-fuel mixing characteristics.

The schematic diagram below illustrates the typical configuration:

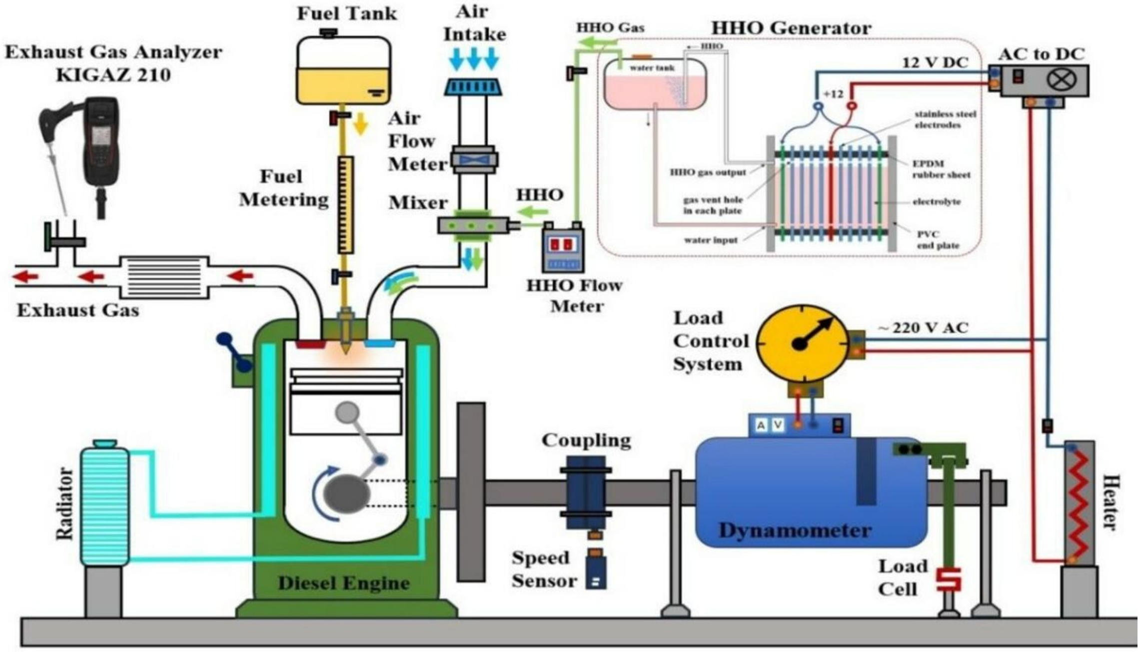


Fig. 2. Engine Setup Schematic Diagram [18]

In a direct injection (DI) engine, diesel is sprayed straight into the combustion chamber at high pressure, breaking into fine droplets that mix with the air. When HHO gas is supplied through the intake manifold or directly into the cylinder, it adds extra hydrogen and oxygen. This addition helps the flame spread faster, improves combustion efficiency, and raises thermal performance. Hydrogen in HHO burns with a relatively high flame speed (about 2.7–3.0 m/s), which shortens ignition delay and allows the diesel droplets to burn more quickly and steadily. The oxygen content further supports fuel oxidation, leading to lower emissions of carbon monoxide (CO), hydrocarbons (HC) and particulate emissions.

The presence of the HHO also influences combustion phasing and peak cylinder pressures, slightly increasing thermal efficiency without requiring major engine modifications. Direct injection ensures that diesel and HHO interact in the combustion chamber under optimal conditions, allowing controlled ignition timing, better quenching of local hot spots, and reduced unburned fuel residues. This setup enables a detailed analysis of HHO's impact on performance parameter such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), torque, power output & the exhaust emissions under changing engine loads and speeds.

Overall, experimental setup of HHO integration in a DI diesel engine provides a practical framework to evaluate sustainable performance enhancement, emission reduction, and economic feasibility while retaining engine reliability and operational safety.

Key Components:

1. **HHO Gas Generator**: This unit employs electrolysis to split water into hydrogen + oxygen gases. The generated HHO is directed in engine's intake manifold.
2. **Electrolyte Solution**: Typically, a mixture of distilled water and a small amount of electrolyte (such as sodium hydroxide) is used to facilitate the electrolysis process.
3. **Power Supply**: A DC power source is required to provide the necessary current for the electrolysis process.
4. **Engine Intake Manifold**: HHO gas is supplied into the intake air, where it blends with the airflow before moving into the combustion chamber.
5. **Combustion Chamber**: Inside the engine, the HHO-enriched air-fuel mixture undergoes combustion, leading to improved fuel efficiency and reduced emissions.

Operation:

- The HHO gas generator operates when the engine is running, ensuring that gas production is synchronized with engine demand.
- The HHO gas is supplied into the intake manifold, where it mixes with the incoming air.
- This mixture enters the combustion chamber, where the hydrogen component of the HHO gas aids in more complete combustion of the fuel, leading to enhanced engine performance and reduced emissions.

Table 4. Input Parameters (Controllable/Measurable during Setup)

Parameter	**Description**
Diesel Fuel Flow Rate	The quantity of diesel injected into the engine, controlled using a burette setup.
HHO Gas Flow Rate	Controlled flow of HHO gas from the generator to the intake manifold (measured via rotameter).
Air Flow Rate	The quantity of intake air drawn into the engine, typically measured using an orifice meter.
Crank Angle (TDC Timing)	The piston's position relative to Top Dead Center, critical for ignition timing.
Engine Load	Applied using an eddy current dynamometer, can be varied for part-load and full-load testing.
Cooling Water Flow Rate	Regulated cooling to maintain engine and exhaust gas temperatures.

Electrolyzer Input Voltage and Current	Electrical power supplied to the HHO generator, affecting gas production rate.
Electrolyte Concentration	The molarity of KOH/NaOH solution used for electrolysis affects efficiency and gas purity.
Ambient Conditions	Temperature, pressure, and humidity, which can influence air-fuel mixing and combustion.

Table 5. Output Parameters (Controllable/Measurable during Setup)

Parameter	Description
Brake Power (BP)	The engine's power was recorded using a dynamometer.
Brake Specific Fuel Consumption (BSFC)	Fuel efficiency is measured by how much fuel the engine uses to generate one unit of brake power.
Brake Thermal Efficiency (BTE)	Ratio of the engine power output to the energy input from fuel.
Exhaust Gas Temperature (EGT)	Indicates combustion efficiency and potential energy losses.
Cylinder Pressure	Measured via in-cylinder pressure sensor, helps analyze combustion phasing.
Emission Levels	Measured using gas analyzers for: CO (Carbon Monoxide), HC (Unburned Hydrocarbons) CO_2 (Carbon Dioxide), NO_x (Nitrogen Oxides), O_2 (Residual Oxygen) and Smoke

5. Effect of HHO adding to Diesel Engine Performance

HHO supplementation in diesel engines offers a promising approach for achieving better combustion efficiency. Experimental results indicate notable gains in engine performance parameters, though effects on NO_x emissions require careful consideration.

Table 6. HHO performance on diesel engine results

Ref	HHO / Oxyhydrogen Addition / Flow / Blend	Engine / Load / Speed / Fuel	Improvement in Performance (BTE, Power, Torque etc.)	Reduction / Change in Emissions / Fuel Consumption etc.
[16] (2023)	HHO flow rates of **0.25, 0.50, 0.75 L/min** added to diesel	CI engine, load ~80% (10 kg), various loads	**+6.54%** increase in BTE at 0.75 L/min, also improved peak pressure & pressure rise.	BSFC / specific energy consumption improved by ~ **6.0%**, CO, HC, Smoke reduced by ~58%, ~60%, ~49% respectively. NO_x slightly increased.
[8] (2023)	Optimum HHO gas flow ~ **3 LPM** added to biodiesel blends	Diesel + biodiesel blends, full load, 1500 rpm etc.	Improvement in BTE (exact % not always large but positive) and in-cylinder pressure & combustion characteristics improved.	CO and unburnt hydrocarbon reduced significantly; NO_x increases with increasing HHO flow.

[5] (2024)	Use of HHO with 20% Jatropha methyl ester (JME20) blend; HHO induction under dual-fuel mode	Diesel engine, 50% load etc.	Brake Thermal Efficiency increased by **1.25%** above baseline diesel at optimal combination (JME20 + HHO).	Smoke, CO, HC emissions reduced by ~22.22%, 25%, and 27.27% respectively vs diesel baseline. NO_x increased.
[6] (2024)	Variation in oxy-hydrogen injector sizes; different HHO injection rates under low & medium loads	Diesel dual-fuel engine at speeds 1800-2200 rpm etc.	Torque, thermal efficiency improved especially at low/medium loads.	CO, CO_2 emissions lower; specific fuel consumption lower at optimal injector sizes.
[7] (2020)	HHO flow of 6 & 10 standard cubic feet/hour (SCFH)	Small CID engine, varying speed up to ~3000 rpm	Max increase in torque & power: **~22.4%**; Efficiency up by **≈19.4%** at optimal speed (2600 rpm).	Efficiency increases; CO, HC etc. reduced; BSFC improved.
[15] (2025)	HHO flows of **1.03, 1.31, 1.69 slpm** with different KOH electrolyte concentrations	Real road test, M2 class vehicle, extra-urban driving cycle	Not directly BTE figures but fuel consumption reduction of **5-8%** with increasing HHO gas flow and more KOH concentration.	Fuel consumption dropped 5-8%; emissions not fully reported in that study.
[12] (2022)	HHO enriched fuel with Moringa oleifera biodiesel blends (20% & 40% blends)	CI engine, varying loads, speed ~1500 rpm etc.	Improved BTE compared to biodiesel-only blends; performance closer to diesel.	BSFC reduced compared with biodiesel alone; emissions of CO, HC reduced; NO_x reduces at low biodiesel blend enriched with HHO.
[14] (2025)	Self-generated HHO, under different operating conditions	CI engine, various loads etc.	Positive effect on Brake Thermal Efficiency; increases depend on load (not always huge).	BSFC reduced for many conditions; emission improvements in some cases.
[20] (2020)	Same as [7] essentially, H6 & H10 SCFH	Small engine, multiple speeds	Minimum increase in efficiency: ~2.5% (H6) & ~10.5% (H10); torque +8% (H6) & +15% (H10).	BSFC better; emissions improved; effect more significant at higher rpm.
[10] (2025)	Use of improved HHO generator in testbed engine	Diesel or generator-type engine, testing fuel efficiency etc.	Measured improvement in fuel efficiency; exact BTE increase	Reduced fuel consumption; emissions (CO, possibly HC) lower;

			modest but significant.	details depend on experimental setup.

Table 6. Average performance result

Metric	Approximate Average Improvement
Brake Thermal Efficiency-BTE	**~6-10%** increase
Specific Fuel Consumption / BSFC / Specific Energy Consumption	**~5-8%** reduction
Power / Torque	**~10-20%** increase (best values around 20-22%)
Emissions (CO, HC, Smoke etc.)	CO, HC, Smoke reductions often between **40-60%** in high HHO flow/optimal conditions; NO$_x$ often increases slightly

From the collected recent studies:

- HHO addition generally improves diesel/CI engine performance notably in Brake Thermal Efficiency, and reduces fuel consumption (BSFC) under proper flow rates and loads.
- Emissions (CO, HC, Smoke) often drop significantly under optimal HHO addition; NO$_x$ tends to increase slightly but is often manageable or can be mitigated via operating parameters.
- The average improvements are strong enough to build the argument that **HHO is good for diesel engines**, especially when optimized for flow rate, load, and fuel type.

7. Economic Feasibility of HHO Adoption in Diesel Engines

The economic viability of integrating HHO systems into diesel engines depends on initial cost, operational cost, fuel savings, and payback period.

- Initial Investment: Commercially available small-scale HHO generators cost between ₹16,000–₹40,000 depending on capacity and electrolyzer design [5], [6].
- Fuel Savings: Recent experimental studies report a 5–15% reduction in diesel consumption with optimized HHO flow rates [12], [15]. For instance, a medium-duty truck consuming ~20 liters/day can save 1.5–3.0 liters/day, equivalent to ₹135–₹270/day (assuming ₹90/liter diesel price in India).
- Payback Period: With daily fuel savings of ₹4,000–₹8,000 per month, the payback period is 6–10 months for commercial vehicles covering >2,500 km/month [5].
- Operational Costs: Negligible—HHO generators consume distilled water (≈100–200 mL/hour) and a small quantity of KOH/NaOH electrolyte, while electricity is supplied from the vehicle's alternator.
- Maintenance Costs: Limited to periodic water refilling and electrolyzer cleaning every 200–300 operating hours. Electrode lifespan is typically 2–3 years under pulse electrolysis operation [16], [17].
- Scalability: Feasible for both light-duty and heavy-duty applications. Retrofitting existing fleets can yield substantial annual fuel savings of ₹50,000–₹1,00,000 per vehicle, depending on usage.

Overall, the economic case for HHO adoption is favorable for commercial transport and agricultural machinery, with quick payback and long-term cost savings.

8. Challenges of Using HHO in Diesel Engines in India

Despite promising results, India-specific challenges remain significant:

1. Fuel Quality Variability

  - Indian diesel often contains 30–50 ppm sulfur (despite BS-VI norms targeting ≤10 ppm).
  - Sulfur and impurities increase electrode fouling and reduce HHO generator lifespan by 20–30% [19].
2. Infrastructure Gaps
   - Currently, there are <10 companies in India producing HHO kits at scale, with limited after-sales service.
   - Lack of trained technicians restricts adoption in rural areas where >60% of diesel engines are deployed for agriculture.
3. Regulatory Barriers
   - There are no established certification standards from the Bureau of Indian Standards (BIS) or the Automotive Research Association of India (ARAI) for retrofitting vehicles with HHO systems.
   - This regulatory vacuum hinders large-scale commercialization and prevents Original Equipment Manufacturers (OEMs) from adopting the technology.
4. Public Awareness and Acceptance
   - Surveys show <25% of vehicle owners are aware of HHO technology.
   - Perceived risks of "hydrogen explosions" lead to hesitation, despite on-demand generation being far safer than compressed hydrogen storage [8], [9].
5. Engine Durability and Long-Term Testing
   - While short-term tests (≤200 hours) show improved Brake Thermal Efficiency (BTE) and reduced emissions, long-term impacts on piston rings, injector tips, and cylinder liners remain underexplored.
   - Studies suggest potential for higher cylinder pressures (up to +8–12%) with HHO addition, which may accelerate wear if not controlled [16].

Addressing these challenges requires policy support, localized manufacturing, training programs, and long-duration field trials under Indian operating conditions.

9. Conclusion

The integration of HHO (oxyhydrogen) gas into diesel engines demonstrates a sustainable and practical approach for enhancing engine performance and reducing emissions in India. HHO gas has emerged as a practical alternative for enhancing diesel engine working and reducing the emissions without extensive engine modification or infrastructure overhaul. Experimental and literature studies indicate an average 6–10% increase in Brake Thermal Efficiency (BTE), 5–8% reduction in Specific Fuel Consumption (BSFC), and 10–20% improvement in engine power and torque under optimal HHO supplementation. Emissions of CO, HC, and smoke decrease by 40–60%, while NO_x experiences only a minor increase, which can be managed through optimized operating conditions.

HHO adoption offers significant economic benefits: for a medium-duty vehicle consuming ~20 liters/day of diesel, fuel savings of 1.5–3.0 liters/day are achievable, translating to ₹1,500–3,000 per month, with a payback period of 6–10 months. Importantly, HHO systems can be retrofitted to existing diesel engines without major modifications, using on-demand pulse electrolysis generators, making it feasible for widespread adoption in commercial, agricultural, and public transportation sectors.

In the Indian context, HHO supplementation aligns with sustainable development goals by reducing fuel consumption, lowering carbon footprint, and improving air quality, while being cost-effective and safe. With appropriate policy support, localized manufacturing, and training programs, HHO technology can provide an immediate and practical solution to enhance diesel engine efficiency and environmental performance across the country.

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