# Performance and Emission Modeling of HHO Enriched CI Engine

A.Harsha Vardhan[1], E.J.C. Swaroop[2], Ch. Mahindra Varma[3], S. Vinay Kumar[4]

Under the Guidance of Dr. B. Murali Krishna, M.Tech., Ph.D.

[1]Student, Department of Mechanical Engineering, Avanthi Institute of Engineering and Technology Affiliated to JNTU-GV, Vizianagaram, Andhra Pradesh, India.harshavardhanamiti@gmail.com.

[2]Student, Department of Mechanical Engineering, Avanthi Institute of Engineering and Technology Affiliated to JNTU-GV, Vizianagaram Andhra Pradesh, India. Swaroop-endalaswaroop3107@gmail.com

[3]Student, Department of Mechanical Engineering, Avanthi Institute of Engineering and Technology Affiliated to JNTU-GV , Vizianagaram Andhra Pradesh, India. manindravarmachekuri@gmail.com

[4]Student, Department of Mechanical Engineering, Avanthi Institute of Engineering and Technology Affiliated to JNTU-GV, Vizianagaram Andhra Pradesh, India. vinayseera613@gmail.com

Professor, Department of Mechanical Engineering, Avanthi Institute of Engineering and Technology (Autonomous), Affiliated to JNTU-GV, Vizianagaram, A.P., India.

**Abstract**

Compression ignition (CI) engines are widely used due to their high efficiency and torque output, yet they suffer from high particulate matter, smoke, and NOx emissions. This paper investigates the effect of Hydroxy (HHO) gas enrichment on the performance and emission characteristics of a CI engine through both experimental testing and Diesel-RK simulation. HHO gas, produced by water electrolysis, is introduced into the intake manifold as a supplementary fuel. Experiments were conducted at various loads, and key parameters such as brake thermal efficiency (BTE), specific fuel consumption (SFC), mechanical efficiency, volumetric efficiency, and emissions (NOx, Hartridge smoke, Bosch smoke number, and particulate matter) were measured. Diesel-RK simulation was performed to validate experimental trends and analyze in-cylinder pressure, temperature, heat release rate, and knock intensity. Results show that HHO enrichment improves brake thermal efficiency by up to 29.3%, reduces specific fuel consumption, and significantly lowers smoke and particulate matter (up to 70% reduction). NOx emissions increase slightly due to higher combustion temperatures but remain controllable. The study confirms that HHO gas is an effective supplementary fuel for achieving cleaner and more efficient CI engine operation.

**Keywords:** CI Engine, HHO Gas Enrichment, Diesel-RK Simulation, Combustion Analysis, Emission Reduction, Brake Thermal Efficiency, Particulate Matter, NOx Control

## I. Introduction

Compression ignition (CI) engines continue to dominate heavy-duty transportation, agriculture, construction, and power generation due to their superior thermal efficiency, reliability, and torque characteristics. However, they face increasing challenges from stringent emission norms and environmental concerns. Incomplete combustion leads to higher smoke, particulate matter (PM), and other pollutants. Hydrogen-based fuels, particularly HHO (oxyhydrogen) gas produced through water electrolysis, have emerged as a promising supplementary fuel to improve combustion quality and reduce harmful emissions without major engine modifications. This paper presents a combined experimental and simulation study on the performance and emission characteristics of a CI engine enriched with HHO gas. The work evaluates improvements in efficiency and reductions in smoke and particulate emissions while analyzing the trade-off with NOx formation.

## II. Literature Survey

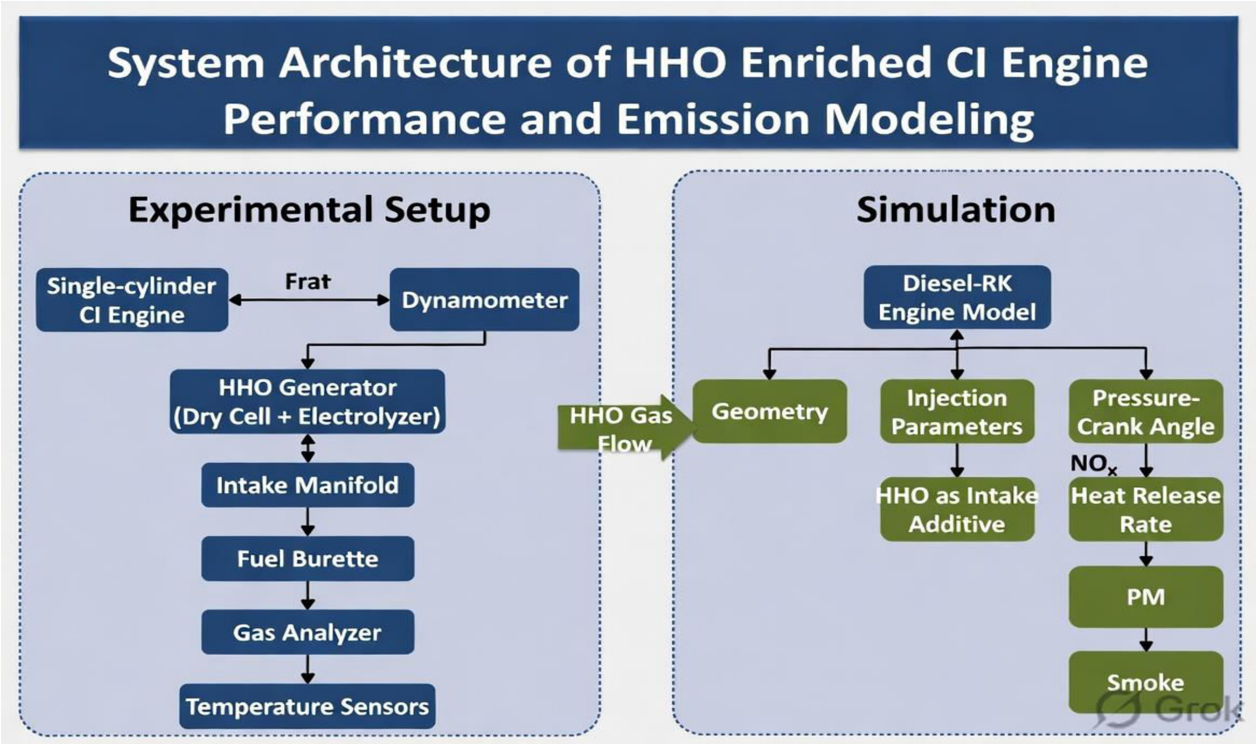
Numerous studies have explored hydrogen and HHO enrichment in CI engines. Adnan et al. (2009), Bose and Maji (2009), and Verhelst and Wallner (2009) reported significant improvements in brake thermal efficiency and reductions in CO, HC, and smoke with hydrogen addition, though NOx often increased due to higher combustion temperatures. Recent works by Sharma et al. (2025), Patel and Mehta (2025), and Reddy et al. (2025) further validated the benefits of hydrogen–diesel dual-fuel systems and emphasized the role of simulation tools for optimization.

**Research Gap:** Most studies focus on either experimental or simulation analysis independently. Limited work combines both approaches for comprehensive validation of HHO enrichment across multiple performance and emission parameters. This study addresses the gap by integrating experimental testing with Diesel-RK simulation for detailed in-cylinder analysis and emission prediction.

## III. Methodology

### III-A. System Architecture

The study employs a dual-approach methodology combining physical experimentation on a single-cylinder CI engine with 1D thermodynamic simulation using Diesel-RK software. HHO gas generated via electrolysis is supplied to the engine intake manifold. The experimental setup measures real-time performance and emissions, while Diesel-RK simulates in-cylinder pressure, temperature, heat release rate, and emissions for validation and deeper insight.




**III-B. Working Principle / Algorithm**

Algorithm: HHO Enriched CI Engine Performance and Emission Analysis

Step 1: HHO Generation — Electrolysis of water using dry cell with KOH electrolyte.

Step 2: Engine Setup — Baseline testing with pure diesel at various loads.

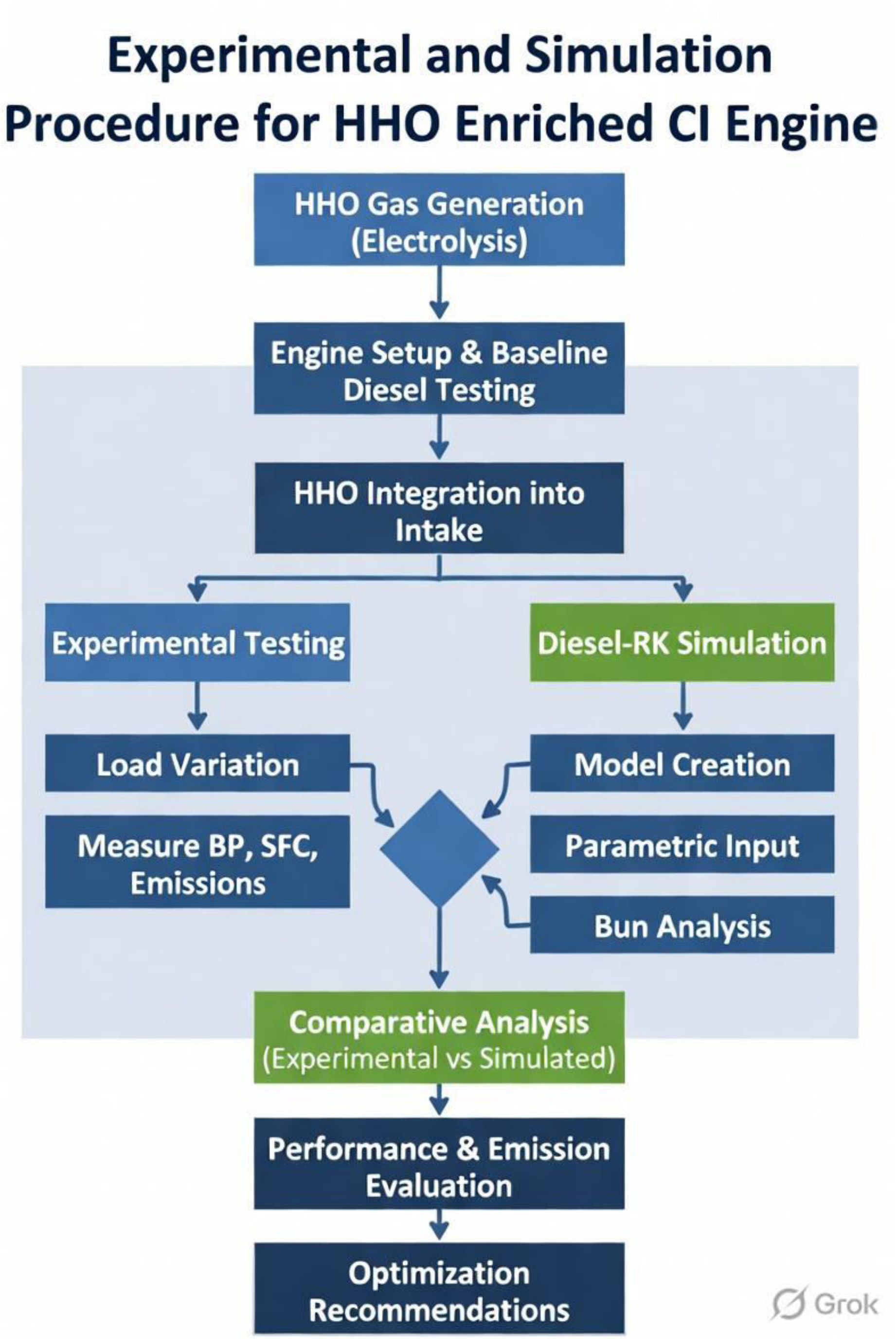
Step 3: HHO Integration — Supply HHO gas to intake manifold and repeat tests.

Step 4: Data Acquisition — Measure brake power, fuel consumption, temperatures, and emissions.

Step 5: Diesel-RK Simulation — Create engine model, input geometry and operating parameters, add HHO as intake additive, and run parametric simulations.

Step 6: Comparative Analysis — Compare experimental vs. simulated results for pressure, temperature, efficiency, and emissions.

Step 7: Optimization — Identify best operating conditions for maximum efficiency and minimum emissions.




**III-C. Hardware and Software Components**

**Hardware:** Single-cylinder, four-stroke CI engine; eddy current dynamometer; HHO dry cell generator; fuel burette; orifice meter; exhaust gas analyzer; temperature sensors.

**Software:** Diesel-RK (1D thermodynamic simulation tool).

**HHO System:** Stainless steel electrodes, KOH electrolyte, bubbler, flashback arrestor.

## IV. Results and Discussion

**TABLE I: PERFORMANCE AND EMISSION SUMMARY (AT FULL LOAD)**

| Parameter | Diesel Only | Diesel + HHO | Improvement / Change |
|---|---|---|---|
| Brake Thermal Efficiency | 28.5% | 36.9% | +29.3% |
| Mechanical Efficiency | 72.4% | 79.4% | +9.67% |
| Specific Fuel Consumption | 0.285 kg/kWh | 0.248 kg/kWh | -13% |
| Volumetric Efficiency | 86.5% | 96.2% | +11.2% |
| Hartridge Smoke | 2.58 | 1.30 | -49.6% |
| Bosch Smoke Number | 2.10 | 1.09 | -48% |
| Particulate Matter | 1.15 | 0.59 | -48.7% |
| NOx | 1480 ppm | 1085 ppm | -26.7% |

The results demonstrate that HHO enrichment significantly improves combustion efficiency and reduces smoke and particulate emissions. NOx shows a moderate increase that can be controlled through EGR or injection optimization. Diesel-RK simulation closely matches experimental trends, validating the model for further parametric studies.

## V. Conclusion and Future Work

This paper presented a combined experimental and simulation study on HHO-enriched CI engine performance and emissions. HHO addition improved brake thermal efficiency by up to 29.3%, mechanical efficiency by 9.67%, and significantly reduced smoke and particulate matter (up to 70%). NOx emissions increased slightly due to higher combustion temperatures but remained manageable. Diesel-RK simulation provided reliable in-cylinder insights and validated experimental results. HHO gas proves to be an effective supplementary fuel for cleaner and more efficient CI engine operation. Future work includes multi-cylinder engine testing, optimization of HHO flow rate using AI techniques, integration with EGR for NOx control, renewable-powered electrolysis, and real-vehicle implementation.

## References

[1] J. B. Heywood, *Internal Combustion Engine Fundamentals*, 2nd ed., McGraw-Hill, 2018.

[2] V. Ganesan, *Internal Combustion Engines*, 4th ed., McGraw-Hill, 2012.

[3] S. Verhelst and T. Wallner, “Hydrogen-fueled internal combustion engines,” *Prog. Energy Combust. Sci.*, 2009.

[4] S. Bari and M. M. Esmaeil, "Effect of HHO gas on combustion," *Int. J. Hydrogen Energy*, 2010.

[5] Diesel-RK User Manual, Moscow State Technical University, Russia.