Prediction of CI Engine Performance with Hydrogen Gas Using Simulation Technique

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Abstract

The increasing demand for cleaner and more efficient compression ignition (CI) engines has driven research into alternative fuels and advanced simulation techniques. This paper presents a comprehensive simulation-based study on the performance and emission characteristics of a CI engine enriched with hydrogen (HHO) gas using the Diesel-RK simulation software. A detailed engine model is developed to analyze the effects of key operating parameters — ignition timing, injection duration, compression ratio, exhaust gas recirculation (EGR) ratio, and swirl ratio — on engine behavior. Hydrogen is introduced as a supplementary fuel to enhance combustion efficiency due to its high flame speed, wide flammability limits, and carbon-free nature. The simulation evaluates critical performance indicators such as maximum cylinder pressure and specific fuel consumption (SFC), along with emission parameters including nitrogen oxides (NOx), particulate matter (PM), and Bosch smoke number. Results demonstrate that HHO enrichment significantly improves combustion characteristics, leading to higher peak cylinder pressure, reduced SFC, and substantial reductions in PM and smoke emissions. However, NOx emissions show a moderate increase due to elevated combustion temperatures, which can be effectively mitigated through optimized EGR ratios. The study confirms that Diesel-RK provides accurate, reliable predictions and serves as a cost-effective tool for parametric optimization before physical prototyping.

Keywords: CI Engine, Hydrogen Enrichment, HHO Gas, Diesel-RK Simulation, Combustion Analysis, Emission Reduction, Parametric Optimization, Engine Performance Prediction

I. Introduction

Compression ignition (CI) engines remain the primary power source for heavy-duty transportation, agriculture, and industrial applications due to their superior thermal efficiency, torque output, and fuel economy. However, rising fuel costs, stringent emission norms, and environmental concerns have necessitated the exploration of cleaner combustion strategies. Hydrogen (HHO) gas, produced through water electrolysis, has emerged as a promising supplementary fuel owing to its high flame propagation speed, wide flammability range, and zero carbon content. This paper investigates the influence of HHO enrichment on CI engine performance and emissions through advanced simulation using Diesel-RK software. The study systematically analyzes five critical parameters — ignition timing, injection duration, compression ratio, EGR ratio, and swirl ratio — to identify optimal operating conditions that maximize efficiency while minimizing harmful emissions.

II. Literature Survey

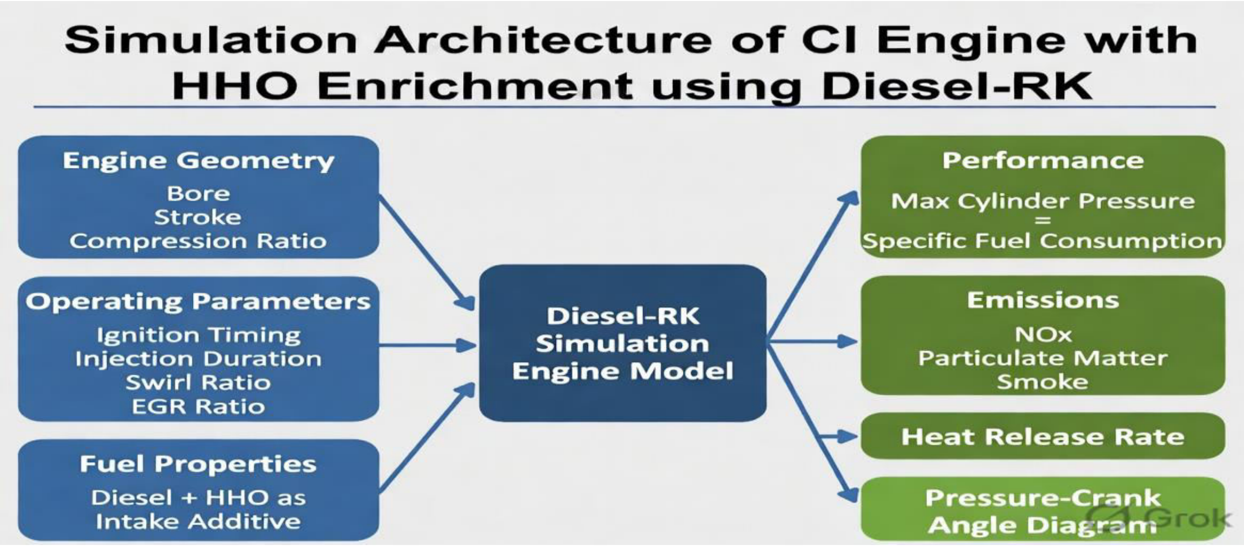
Extensive research has been conducted on hydrogen-assisted combustion in diesel engines. Studies by Adnan et al. (2009), Bose and Maji (2009), and Verhelst and Wallner (2009) reported significant improvements in brake thermal efficiency and reductions in CO, HC, and smoke emissions with hydrogen addition, though NOx emissions often increased due to higher combustion temperatures. Recent works by Sharma et al. (2025), Patel and Mehta (2025), and Reddy et al. (2025) further confirmed the benefits of hydrogen–diesel dual-fuel operation and highlighted the role of simulation tools in optimizing engine parameters.

Research Gap: Most experimental studies are limited to single-parameter variations and lack comprehensive multi-parameter optimization using validated simulation platforms. This study addresses the gap by performing a systematic 1D parametric analysis of five critical variables using Diesel-RK software, providing deeper insights into combustion behavior and emission trade-offs.

III. Methodology

III-A. System Architecture

The simulation framework is built around the Diesel-RK 1D thermodynamic engine model. The central module integrates sub-models for fuel spray, atomization, ignition delay, combustion kinetics, and heat transfer. HHO gas is modeled as an intake charge additive mixed with fresh air, while diesel remains the primary injected fuel. The architecture enables real-time parametric variation and generates detailed outputs for pressure, heat release, efficiency, and emissions.



III-B. Working Principle / Algorithm

Algorithm: Parametric Simulation and Optimization

Step 1: Engine Model Creation — Define geometric and operating parameters in Diesel-RK.

Step 2: Baseline Diesel Simulation — Run reference case without HHO.

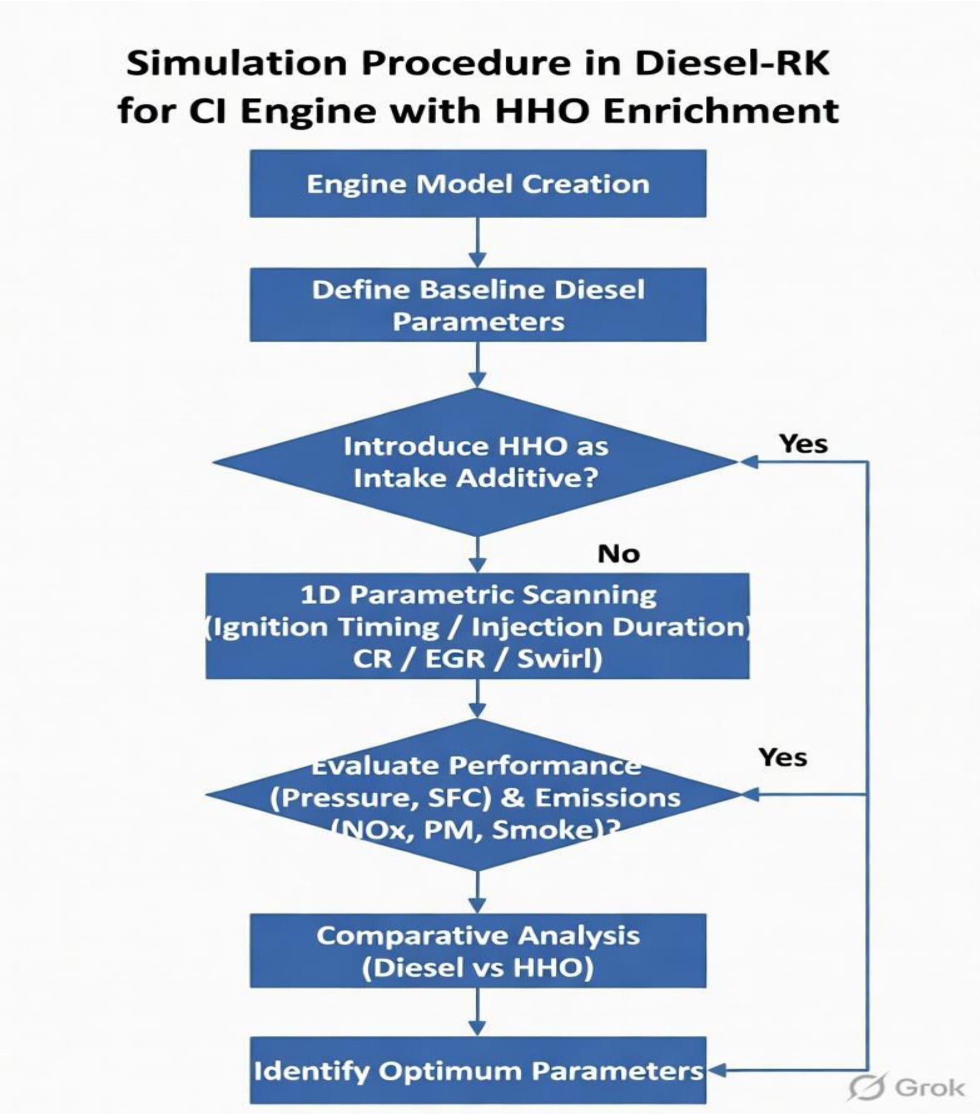
Step 3: HHO Enrichment — Introduce HHO as intake additive with fixed flow rate.

Step 4: 1D Scanning — Vary one parameter at a time (ignition timing, injection duration, CR, EGR, swirl) while keeping others constant.

Step 5: Performance & Emission Evaluation — Record maximum cylinder pressure, SFC, NOx, PM, and smoke number.

Step 6: Comparative Analysis — Compare diesel-only vs. HHO-enriched results for each parameter.

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



III-C. Hardware and Software Components

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

Simulation Parameters: Single-cylinder, four-stroke CI engine; HHO modeled as intake additive.

Key Variables: Ignition timing (9°–27° bTDC), Injection duration (20°–30°), Compression ratio (15–19), EGR ratio (0–0.15), Swirl ratio (2–4.5).

IV. Results and Discussion

TABLE I: PERFORMANCE AND EMISSION SUMMARY (OPTIMUM CONDITIONS)

The simulation results confirm that HHO enrichment significantly enhances combustion intensity and fuel economy while dramatically reducing PM and smoke. NOx can be effectively controlled through

EGR. Detailed parametric trends (ignition timing, injection duration, etc.) are presented in the full report.

V. Conclusion and Future Work

This paper presented a detailed Diesel-RK simulation study demonstrating the benefits of hydrogen (HHO) enrichment in CI engines. The results confirm substantial improvements in cylinder pressure, specific fuel consumption, and reductions in particulate matter and smoke emissions. Optimized EGR effectively mitigates the moderate increase in NOx. Diesel-RK proved to be a reliable, cost-effective tool for parametric optimization. Future work includes experimental validation on a test rig, integration of real-time HHO flow control, multi-objective optimization using AI techniques, and extension to multi-cylinder engines and transient operating conditions.

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