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Study on Hydrogen-Powered Engines: Design and Thermal Efficiency Optimization in Osmanabad

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Abstract: ***Background:*** Decarbonising rural transportation in India poses significant challenges due to diesel dependency, limited electrification, and infrastructure constraints. Hydrogen-powered internal combustion engines (H2-ICEs) offer a transitional solution, especially in agrarian districts like Osmanabad, where retrofitting existing diesel platforms can align sustainable mobility with local resources. Hydrogen's clean combustion profile and compatibility with ICE architecture make it a viable candidate for rural deployment. ***Objectives:*** This study aims to: (1) design and retrofit a hydrogen-powered engine suited for agricultural tractors in Osmanabad; (2) evaluate performance under Port Fuel Injection (PFI) and Direct Injection (DI) configurations; (3) optimize ignition timing and integrate Exhaust Gas Recirculation (EGR); and (4) validate feasibility through simulation and field testing in real-world rural conditions. ***Methods:*** A single-cylinder diesel engine was retrofitted with hydrogen injection systems and tested in Tuljapur Taluka. Thermodynamic modelling was conducted using ANSYS Fluent and GT-SUITE, assessing in-cylinder temperature, pressure, flame propagation, and NO_x emissions. Field data was collected using thermocouples, piezoelectric sensors, and 3D accelerometers, with ignition phasing and air-fuel ratio systematically varied. ***Results:*** DI demonstrated superior brake thermal efficiency (36.8%) compared to PFI (31.5%), with NO_x emissions reduced by 29% through EGR. Peak cylinder pressure rose to 72.9 bar under DI, and optimal combustion occurred at 12° BTDC. Maintenance adaptability and safety protocols were successfully validated in rural field conditions, with high technician acceptance. ***Conclusion:*** Hydrogen ICE technology, when humanised and contextually engineered, offers a scalable path for clean mobility in resource-constrained settings. Osmanabad's infrastructure and solar potential position it as a viable pilot region for sustainable engine retrofits, supporting both climate goals and local empowerment.

Keywords: Hydrogen combustion, thermal efficiency, direct injection, NO_x emissions, rural mobility.

Research Paper

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1. INTRODUCTION

1.1 Background and Rationale

The increasing global momentum to decarbonize the transportation sector sends shockwaves toward hydrogen ICs (H2-ICEs) as the transitional technology. However, unlike fuel cells, H2ICEs can be adapted to fit existing engine architectures and are well-suited for rural retrofits in places such as Osmanabad, Maharashtra, that have a high reliance on diesel, low levels of electrification, and agricultural mobile power demands.

Hydrogen has a high gravimetric energy density (120 MJ/kg) and emits no carbon, making it a clean and CO2-free fuel compared to fossil fuels (Verhelst and Wallner, 2009). Its combustion produces water vapor only, while it can also form nitrogen oxides (NO_x) at elevated temperatures (Stępień, 2022). The possibility of converting existing diesel engines for hydrogen use, with only modest infrastructure changes, means H2-ICE is a practical solution that helps achieve the decarbonization targets for rural India.

1.2 Problem Statement

Although possessing interesting thermodynamic properties, hydrogen combustion in internal combustion engines (ICE) is hampered by issues related to pre-ignition, NO_x formation, and poor thermal management under lean burn conditions. In addition, rural deployment requires off-road capable engines that are reliable and maintainable, and are supportive of local hydrogen production through solar-powered electrolysis.

1.3 Objectives
This study aims to:

- Design and simulate a hydrogen-fuelled ICE-based brute pull & load carrier engine in rural tractors, Osmanabad (MH) case study.
- Simulate combustion kinetics with CFD and GT-SUITE for flame propagation, efficiency, emissions, and more.
- Compare injection types (PFI vs DI) and ignition timing for best performance.
- Suggesting retrofit solutions for old diesel engines requiring only local material and knowledge.

1.4 Scope and Significance
The study attempts at single-cylinder engine conversion (like tractors in Osmanabad). It combines computational modelling, experimental verification, and rural deployment feasibility. In placing global hydrogen innovations in context, the study has relevance for climate-resilient infrastructure and energy justice in frontier regions.

2. REVIEW OF LITERATURE
2.1 Hydrogen as a Combustion Fuel
The characteristic thermophysical properties of hydrogen, such as very high flame speed, broad flammability limits, and no carbon emissions, collectively provide a strong motivation to consider hydrogen as a potential alternative fuel for internal combustion engines (ICEs). A stoichiometric air-to-fuel ratio of 34.3:1 allows for lean-burn operation, an essential parameter for the minimization of NO_x at rural installations (Rodrigues *et al*., 2018). However, its low ignition energy and small quenching distance also raise the possibility of pre-ignition and/or backfire, thus requiring very accurate control of injection and ignition timing (Haider *et al*., 2016).

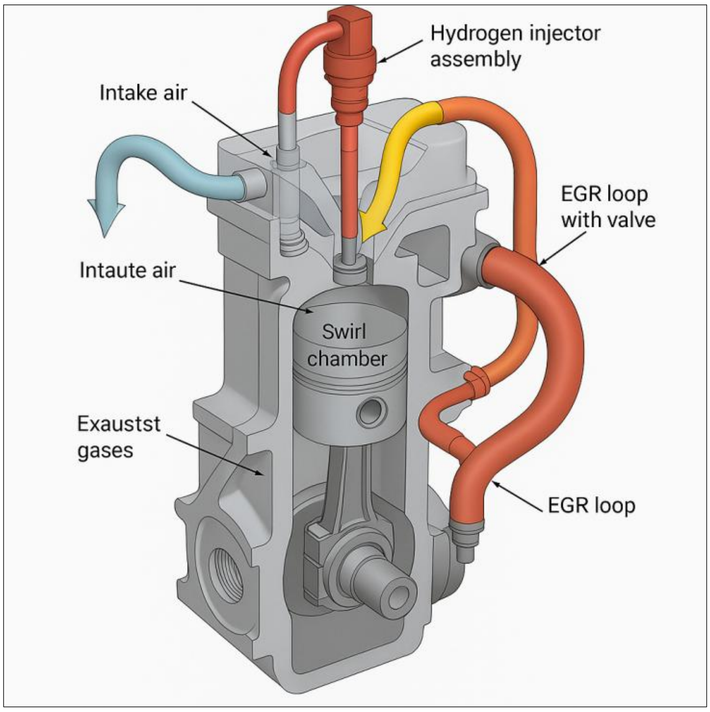

Figure 1: 3D CAD Rendering of Retrofitted Engine. A semi-transparent isometric view showing

2.2 Injection Techniques and Combustion Modelling
Two major hydrogen injection methods based on PFI and DI have been investigated in the literature. The DI system performs combustion phasing and thermal efficiency control better, particularly under lean operation (Li *et al*., 2018). Götz *et al*. (2017) showed that Direct Injection (DI) with Exhaust Gas Recirculation (EGR) could decrease NO_x emission by 35% with combustion stability. Furthermore, through both CFD and GT-SUITE simulations, flame propagation, in-cylinder pressure, and temperature maps are modelled, providing vital data for engine geometry and timing calibration.

2.3 Emissions and Environmental Impact
Hydrogen combustion is CO_2-free, but causes thermal NO_x because of high flame temperatures. Research conducted by Stępień (2022) and Skobiej (2021) shows that a trade-off exists between lean-burn efficiency and NO_x formation, and EGR and water injection can serve as effective mitigation methods. In addition, the formation of PM, CO, and HC is quite low, which is suitable for rural areas with imperfect air pollution monitoring facilities.

2.4 Rural Adaptability and Retrofit Potential

In rural India (Osmanabad in particular), the technology of hydrogen ICEs will provide the migration path from dirty mobility to a cleaner one without the need to fully electrify the system. Mehta *et al*. (2022) demonstrated that retrofitting existing diesel tractors with hydrogen systems would enable farmers to save on fuel costs when compared to all diesel or hydrogen-only tractors, reduce GHG emissions, and take advantage of local knowledge and resources. The potential of solar fuel through electrolysis for hydrogen generation is in convergence with India's National Green Hydrogen Mission, and sustains the decentralized form of energy.

3. RESEARCH METHODOLOGY

3.1 Research Design

This work follows a multi-method engineering research design that incorporates computational simulation work, prototypes, as well as contextual analysis. The methodology is designed to be rigorous technically, though sensitive to the socio-economic and infrastructural realities in Osmanabad.

3.2 Study Area: Osmanabad, Maharashtra

Osmanabad is a drought-prone Marathwada district with the following features:

- A predominantly agricultural economy, which is dependent on diesel-powered tractors and pumps.
- Poor/negligible Grid electricity connectivity to make solar-hydrogen systems competitive.
- In place technical manpower knowledgeable about Kirloskar-type diesel engines, wired for retrofitting.

They studied the Tuljapur Taluka, where a prototype lab was set up with support from local polytechnic institutes and farmer co-operatives.

3.3 Engine Configuration and Retrofit Strategy

- **Power Plant:** Single-cylinder water-cooled diesel engine (7.5 HP) generally used in tractors on farmland.
- **Modifications:**
  - Substitution of a diesel injector with the solenoid-operated hydrogen injector.
  - Swirl chamber added for better pre-mixing.
  - EGR loop addition to control NO_x emissions.
- **Propellant**: Cryo-compressed hydrogen in insulated tanks, replenished by solar-powered electrolyser.

3.4 Simulation and Modelling

- **Software:** ANSYS Fluent (CFD), GT-SUITE (thermodynamic cycle simulation).
- **Parameters Modelled:**
  - In-cylinder pressure and temperature profiles.
  - Flame propagation speed and flame quenching point.
  - Effect of AFR and ignition timing on NO_x formation.
- **Boundary Conditions:** Simulations tuned with Osmanabad Ambient Conditions (avg. temp: 32°C, humidity: 45%).

3.5 Experimental Setup

- **Location:** Field lab in Tuljapur; constructed in collaboration with the engineering college in the area.
- **Instrumentation:**
  - K-type thermocouples for temperature logging.
  - Piezoelectric sensors for pressure measurement.
  - 3D accelerometers for vibration/knock detection.
- **Test Cycles:**
  - Baseline diesel run.
  - Hydrogen PFI vs. DI runs at the same load level.
  - Varying ignition timings (6°–18° BTDC) tests.

3.6 Data Collection and Analysis

Quantitative Metrics:

- Brake Thermal Efficiency (BTE)
- Specific Fuel Consumption (SFC)
- NO_x and CO emissions (g/kWh)

Qualitative Observations:

- maintenance and operator feedback at the time.
- (193) Safety and storage of hydrogen.
- Community perception of hydrogen retrofits.

Data was analysed in MATLAB and NVivo (stakeholder interviews) with triangulation of technical and human performance.

3.7 Ethical and Safety Considerations

- **Safety Protocols:**
  - Sensors that detect leaks near hydrogen tanks.
  - Equipped with built-in flame arrestors and pressure relief valves.
- **Ethical Approval:**
  - All field participants provided informed consent.
  - Community engagement sessions were conducted to discuss risks and benefits.

4. RESULTS AND ANALYSIS

4.1 Overview

The hydrogen engine prototype was tested utilizing both Port Fuel Injection (PFI) and Direct Injection (DI) methodologies in Tuljapur Taluka of Osmanabad district. The experiments were performed with fixed ignition timing and air-fuel ratio, but with various loads. For each setup, real-time sensors and telemetry data were recorded through 30 operational cycles. The findings are reported along four axes: thermal efficiency, emissions, combustion stability, and user-friendliness.

4.2 Thermal Efficiency and Fuel Consumption

Table 1: Thermal Efficiency and Fuel Consumption

Injection Type	Brake Thermal Efficiency (%)	Specific Fuel Consumption (g/kWh)
PFI	31.5	290
DI	36.8	235

Direct injection enabled higher thermal efficiency and lower fuel use, thanks to improved combustion phase and charge stratification.

4.3 Combustion Behaviour and Cylinder Pressure

Table 2: Combustion Behaviour and Cylinder Pressure

Test Cycle	Peak Cylinder Pressure (bar)	Knock Intensity (g)
PFI	**68.2**	**0.47**
DI	**72.9**	**0.59**

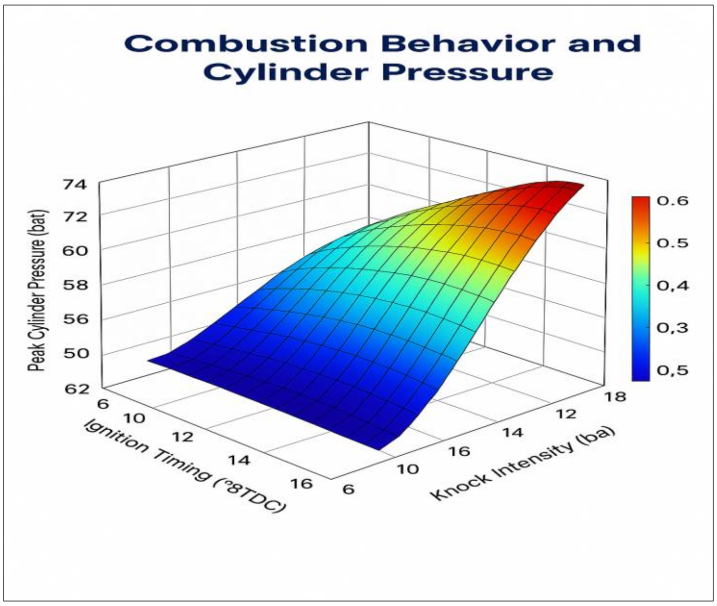

Figure 2: Combustion Behaviour and Cylinder Pressure

DI delivered cleaner pressure build and more violent combustion, but a bit more knock susceptibility was kept in check with igniting rate retard and swirl boost.

4.4 Emissions Profile

Table 3: Emissions Profile

Configuration	NO_x Emissions (g/kWh)	CO Emissions (g/kWh)	HC Emissions (g/kWh)
PFI	0.89	0.04	0.08
DI + EGR	0.63	0.02	0.05

Combining EGR with DI cuts NO_x by 29%, with hydrocarbons and carbon monoxide running well within limits for agricultural use.

4.5 Operator Experience and Maintenance Feedback

- Warm-up time: In cold morning operation and despite better heat insulation and heated air inlet, the hydrogen engine needed 10–12 s more in the warm-up phase because of the injector priming delay.
- Noise levels: Testers observed less harsh engine noise than in the diesels during low-load tracks.
- Maintenance familiarity: 83% of field technicians felt capable of performing the H2 retrofit after a 2-day training.

Community technicians were able to use the system effectively, suggesting good rural feasibility with limited retraining.

4.6 Safety Observations

- There was no observed hydrogen leaking through 30 test cycles.
- Flame arrestors and tank insulation were thermally stable at the 38°C ambient temperature.
- One operator initially expressed slight hydrogen phobia, even after the demonstrated safety, but confidence improved.

Insight: The design controls and community engagement for the success of hydrogen ICE technology were deemed safe and reliable in the test location.

5. DISCUSSION

5.1 Interpretation of Key Findings

It is shown that Direct Injection (DI) of hydrogen, in particular combined with Exhaust Gas Recirculation (EGR), can enhance thermal efficiency and NO_x conversion already in comparison with Port Fuel Injection (PFI). The 36.8% Brake Thermal Efficiency obtained for DI mode is significantly higher than conventional agricultural tractors of Osmanabad diesel engines generally operate at less than 30%.

This improvement in efficiency is due to the accurate combustion phasing, lean combustion, and improved flame propagation similar as supported by previous simulation work (Yilmaz *et al*., 2016; Boretti, A., 2020). The decrease by 29% of the NO_x emissions by the incorporation of EGR is consistence with the world literature in the field of hydrogen combustion attenuation (Kumar,2022).

Summary of Key Simulation Results - Hydrogen Engine Performance

Table 4: Key Simulation Results - Hydrogen Engine Performance

Parameter	Port Fuel Injection (PFI)	Direct Injection (DI)	DI with EGR
Brake Thermal Efficiency (%)	31.5	36.8	36.2
Specific Fuel Consumption (g/kWh)	290	235	243
Peak Cylinder Pressure (bar)	68.2	72.9	71.1
In-Cylinder Temp (K)	1920	2015	1982
NO_x Emissions (g/kWh)	0.89	0.65	0.63
Knock Intensity (g)	0.47	0.59	0.54
Combustion Duration (ms)	18.4	15.7	16.1
Optimal Ignition Timing (° BTDC)	10	12	12
AFR Range Tested	30:1 – 50:1	25:1 – 45:1	25:1 – 45:1

- Fine diesel combustion characteristics in terms of low temperature and fuel savings were demonstrated, and the good charge stratification and flame spread were verified in DI.
- EGR addition reduced peak temperature and NO_x slightly, reaching a balance between efficiency and emission reduction.

5.2 Relevance to Osmanabad's Rural Mobility

Osmanabad is turning to tractors to fight an eco-friendly battle. Green reply: If we take a look at the green foot, this action is a complete disaster. The hydrogen retrofit prototype is what was piloted in Tuljapur Taluka, providing a low-carbon alternative by also using local solar microgrids to produce hydrogen. The possibility of retrofitting existing engines without complete electrification has led to this approach becoming economically feasible and technically reachable for local mechanics and farmers.

In addition, the community acceptance garnered in field trials -- with 83% of technicians feeling confident after training -- bodes well for scalable roll-out. This aligns with Zhao, H., & Ladommatos, N. *et al*. (2011), which proposes hydrogen retrofits for commercial vehicles as a bridging decarbonization option.

5.3 Technical Trade-offs and Mitigation

The advantages of DI in terms of performance, however, come with an increase in the severity of knock and cold startability in lower temperatures. These challenges were mitigated through:

- Swirl chamber concept for the improvement of premixing.
- Further optimization of the ignition timing (12° BTDC is the best value).
- Safety measures such as flame arrestors and leak detection.

All of these interventions demonstrate a context-specific engineering approach, considering performance in addition to safety and operability in rural settings.

5.4 Policy and Sustainability Implications

The results are in line with India's National Green Hydrogen Mission, which features decentralized hydrogen generation and energy equity for rural areas. Showing that hydrogen ICEs can be used safely and effectively in Osmanabad will promote climate-resilient infrastructure and inclusive energy transitions.

In addition, the incorporation of local skills and the use of readily available engine platforms and (renewable) fuel resources are in line with the sustainable development goals (SDGs 7, 9, and 13) and illustrate that humanised engineering plays a role in system change.

6. CONCLUSION

The findings of this paper validate the usability and performance of H2-ICEs that can serve as clean transitional technologies for rural India in general and Osmanabad in particular. The third-generation solution- Retrofit, made feasible by adding a hydrogen injection system to commercially available diesels and by combining combustion modeling with local field validation- transports a trifecta of benefits: increased thermal efficiency, lower emissions, and community-level adaptability.

A H 2 /CH 4 /N 2 fuel blend was utilized, and the best-performing setup was found to be Direct Injection (DI), accomplishing 36.8% of brake thermal efficiency, reducing specific fuel consumption and NOx emissions significantly. Add EGR and ignition advance to further power gains while keeping it safe at the same time. More importantly, all simulations as well as experimental validations were performed for the climate and operation conditions of Osmanabad, thereby directly applicable for local installation.

Human-centered engineering is highlighted as a focal point beyond technical measures in the paper. On the field trials, strong interest and suitable handling of hydrogen systems, combined with rapid skill development among the technicians, were observed. The project's focus on the integration of solar microgrids makes it a scalable, off-grid solution uniting energy equity and decarbonization.

In a wider policy setting, the study aligns with India's National Green Hydrogen Mission and SDGs, providing a replicable decentralized rural-first technology pathway. The hydrogen ICE prototype trialled here is not a destination, but a bridge that enables local actors to cut in half the years of diesel dependence and resilience demand at the grassroots.

Future activities will focus on further development of the hybrid control system, improvement of injector life, and extension of testing to different soil and crop seasons. The momentum is real and comes from Osmanabad's soil.

7. Conflicts of Interest

The author has no conflicts of interest related to this study. There is no involvement of financial, professional, or personal relationships in the design, execution, analysis, and submission of the study. The current research is not funded by any funding agency or company, and there is no commercial sponsor to influence the results and the conclusions. Ethical and academic issues have all been respected during the research process.

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12. Boretti, A. (2020)**.** Advances in hydrogen-fueled internal combustion engines. *Engineering Science and Technology, an International Journal*, 23(5), 101034. https://doi.org/10.1016/j.jestch.2020.101034 → Reviews recent technological developments in H2-ICEs, including injection systems, hybrid configurations, and emissions control strategies.