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# Optimizing NOx reduction in small hydrogen-powered IC engines using water injection and EGR

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## Abstract

With the growing push for low-emission and sustainable transport technologies, hydrogen-fuelled internal combustion engines (HICEs) have become an attractive transitional solution. These engines offer a zero-carbon alternative to conventional fuels, emitting only water vapor during combustion. However, hydrogen's high flame temperature and fast burn rate can lead to elevated nitrogen oxide (NOx) emissions, which remain a significant environmental concern.

This research explores a practical, engine-based solution to this challenge by combining two in-cylinder NOx reduction strategies: water injection and exhaust gas recirculation (EGR). A small single-cylinder spark ignition engine was modified to operate on hydrogen fuel, and then equipped with systems for controlled water injection and EGR. Through a series of experiments at steady-state conditions, the individual and combined effects of these techniques on NOx emissions, combustion temperature, and engine performance were evaluated.

Results showed that water injection effectively lowered in-cylinder peak temperatures by absorbing combustion heat, leading to a noticeable reduction in NOx. EGR contributed by reducing the oxygen content and thermal intensity of the combustion process. When both methods were applied together, NOx emissions were reduced by more than 90% compared to baseline hydrogen operation. The engine continued to run stably, and only a modest drop in thermal efficiency (around 3.5%) was observed.

This dual-strategy approach presents a cost-effective and scalable pathway for reducing NOx emissions in hydrogen engines, particularly for compact mobility applications. It aligns well with global clean-air goals and can accelerate the adoption of hydrogen-powered technologies in sectors where battery-electric solutions may not yet be feasible.

**Keywords:** Hydrogen combustion; Internal combustion engine; NOx reduction; Water injection; Exhaust gas recirculation; Clean energy

## 1. Introduction

The shift toward cleaner, more sustainable energy sources has placed hydrogen at the forefront of the next generation of propulsion technologies. Among its many promising applications, hydrogen-fuelled internal combustion engines (HICEs) offer a practical and immediate alternative to conventional petrol and diesel engines. These engines produce no carbon-based emissions—such as $CO_2$, CO, or unburned hydrocarbons—which makes them particularly attractive in the context of global climate commitments and urban air quality concerns.

Despite this advantage, hydrogen combustion presents a critical challenge: the formation of nitrogen oxides (NOx). Unlike carbon-based emissions, NOx is not a direct by-product of the fuel itself but is produced when nitrogen and

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oxygen in the intake air react at high temperatures during combustion. Hydrogen's inherently high flame temperature and fast combustion speed make this problem even more pronounced, leading to NOx levels that often exceed those of traditional fuels under similar conditions.

Conventional approaches to NOx reduction, such as catalytic after-treatment systems, are often less effective in hydrogen engines—especially when operating under lean-burn conditions. As a result, researchers have turned their attention to in-cylinder strategies that tackle NOx formation at its source. Two of the most promising methods are water injection and exhaust gas recirculation (EGR). Water injection works by absorbing combustion heat, thereby reducing peak flame temperatures. EGR, on the other hand, recirculates a portion of the exhaust gases back into the intake stream, lowering oxygen concentration and reducing combustion intensity.

While both techniques have shown individual success in reducing NOx emissions, relatively few studies have explored their combined impact, especially in small single-cylinder engines used in lightweight transportation applications. This research aims to fill that gap by examining how water injection and EGR—when applied together—can significantly reduce NOx emissions without compromising engine performance.

The goal of this study is to experimentally evaluate the effectiveness of these two strategies using a hydrogen-fuelled spark ignition engine under controlled conditions. In doing so, it aims to provide a practical and scalable solution for reducing NOx emissions in compact hydrogen engine systems, which could be especially valuable in developing clean mobility options for two-wheelers and small utility vehicles.

## 2. Fundamentals of Hydrogen Internal Combustion Engines (HICEs)

### 2.1. Introduction to Hydrogen as a Fuel

Hydrogen stands out as one of the cleanest fuels available today. With a high energy content by weight and zero carbon in its composition, it offers a strong alternative to fossil fuels, especially for applications aiming to drastically cut greenhouse gas emissions. When used in internal combustion engines (ICEs), hydrogen can provide power without producing carbon-based emissions such as $CO_2$ or CO. In many ways, this makes hydrogen an ideal candidate for decarbonizing transportation—particularly through engine retrofitting and near-term mobility solutions.

Unlike conventional fuels, hydrogen burns with a high flame speed and has a wide flammability range, allowing it to combust efficiently over a broader range of air–fuel mixtures. These properties make it suitable for lean-burn operation, which can help improve engine efficiency. However, these same characteristics also introduce certain engineering challenges, such as an increased risk of knock, pre-ignition, and backfire, especially when the fuel-air mixture becomes too rich or uneven.

### 2.2. Basic Operation of Hydrogen-Fuelled Spark-Ignition Engines

Hydrogen engines operate using the same fundamental four-stroke cycle seen in conventional spark-ignition (SI) engines: intake, compression, combustion (power), and exhaust. During the intake stroke, a mixture of hydrogen and air enters the combustion chamber. This mixture is compressed and then ignited by a spark plug, resulting in a rapid release of energy that drives the piston. The exhaust stroke removes the combustion products—mainly water vapor and nitrogen.

While the overall engine architecture remains similar to that of petrol engines, some key modifications are needed to accommodate hydrogen. These include the use of reinforced intake manifolds to prevent flashback, hydrogen-specific injectors or valves to manage fuel delivery, and spark control systems that help prevent early ignition events. Because hydrogen is stored and delivered in gaseous form, it also requires careful handling and leak management for safe operation.

### 2.3. Emissions Profile of Hydrogen Combustion

The standout feature of hydrogen combustion is the absence of carbon emissions. When hydrogen burns, it reacts with oxygen to form water vapor, eliminating pollutants like carbon monoxide, unburned hydrocarbons, and particulate matter. However, the high combustion temperature—often exceeding 2000 K—creates favourable conditions for the formation of nitrogen oxides (NOx). This occurs when nitrogen in the intake air reacts with oxygen at high temperatures through a set of thermal reactions, collectively referred to as the Zeldovich mechanism.

NOx emissions from hydrogen engines are especially problematic during stoichiometric or slightly lean operation, where peak flame temperatures are highest. Controlling these emissions requires strategies that can reduce in-cylinder temperature and limit the presence of reactive oxygen and nitrogen species during combustion.

### 2.4. Combustion Characteristics of Hydrogen

Hydrogen combustion exhibits several properties that set it apart from other fuels:

- High flame speed: Hydrogen burns faster than most conventional fuels, allowing for rapid and efficient combustion.
- Wide flammability range: Hydrogen can ignite in very lean or rich mixtures, giving more flexibility in engine calibration.
- Low ignition energy: Hydrogen requires very little energy to ignite, making it prone to pre-ignition or backfire if not managed properly.
- High diffusivity: Hydrogen disperses quickly, promoting more uniform mixing but also increasing the risk of intake manifold ignition.

These traits allow hydrogen engines to operate efficiently, especially under lean conditions, but also necessitate precise control over ignition timing, fuel delivery, and mixture preparation to avoid unwanted combustion event.

### 2.5. Limitations and Engineering Challenges

Despite the many benefits of hydrogen as a fuel, several practical challenges must be addressed to enable widespread use in internal combustion engines:

- Storage and delivery: Hydrogen's low energy density by volume requires pressurized tanks or advanced storage solutions.
- Combustion control: High flame speed and low ignition energy demand accurate spark timing and fuel metering to avoid knock and backfire.
- NOx emissions: Elevated combustion temperatures lead to increased NOx formation, which must be managed through in-cylinder or exhaust-based techniques.
- Infrastructure: Limited hydrogen fuelling infrastructure poses logistical constraints, particularly in developing regions.

These challenges underscore the need for intelligent engine design and effective combustion control strategies—such as the EGR and water injection systems explored in this study.

### 2.6. Summary

Hydrogen internal combustion engines offer a compelling path toward low-carbon transportation, particularly when deployed in applications that are not yet suitable for full electrification. While these engines eliminate carbon-based emissions, the formation of NOx remains a key environmental hurdle. Understanding hydrogen's combustion behavior and its impact on emissions lays the groundwork for exploring effective NOx reduction strategies. The following chapters examine these techniques—specifically water injection and EGR—through both theoretical and experimental lenses.

## 3. Literature Review

### 3.1. Introduction

Hydrogen-fueled internal combustion engines (HICEs) have emerged as a clean propulsion alternative thanks to their ability to eliminate carbon-based emissions. However, they face one significant drawback—high levels of nitrogen oxides (NOx), formed due to the elevated combustion temperatures associated with hydrogen. To address this challenge, researchers have focused on in-cylinder NOx reduction techniques such as lean-burn operation, exhaust gas recirculation (EGR), water injection, and advanced ignition control. This chapter explores past and current research efforts related to NOx formation and control in hydrogen engines, highlighting what is known, what works, and where knowledge gaps still exist.

### 3.2. NOx Formation in Hydrogen Combustion

The formation of NOx in hydrogen engines primarily occurs through the thermal or Zeldovich mechanism. This pathway becomes significant at flame temperatures above 1800 K—a threshold easily crossed during hydrogen combustion. Verhelst and Wallner (2009) noted that while hydrogen engines offer exceptional fuel cleanliness, they can produce more NOx than gasoline engines under stoichiometric conditions due to their high flame speed and combustion intensity.

Several studies have shown that flame temperature, ignition timing, and mixture composition all directly affect NOx levels. Strategies that target the reduction of peak combustion temperature are therefore seen as the most direct and effective approach.

### 3.3. Lean-Burn Strategy

One of the earliest and most commonly applied methods for reducing NOx in hydrogen engines is lean-burn operation. By using excess air (equivalence ratios less than 1.0), the combustion temperature is lowered, thus reducing NOx formation. Das (2002) demonstrated that hydrogen engines could operate reliably at extremely lean mixtures due to hydrogen's wide flammability range. However, when mixtures become too lean, issues like combustion instability, misfire, and power loss can arise, limiting the extent to which lean-burn strategies can be applied in practical applications.

### 3.4. Exhaust Gas Recirculation (EGR)

EGR is widely used in conventional engines and has also been applied to hydrogen engines to reduce NOx. By reintroducing a portion of the exhaust gas into the intake stream, EGR lowers the oxygen concentration and increases the specific heat of the intake mixture. This results in reduced combustion temperatures and slower reaction rates, both of which help suppress NOx formation.

Singh et al. (2013) found that moderate EGR rates—between 10% and 20%—can lower NOx emissions significantly without degrading engine efficiency. However, excessive EGR levels can destabilize the combustion process and reduce power output, especially in small-displacement engines.

### 3.5. Water Injection

Water injection is another technique gaining attention for in-cylinder NOx reduction. When water is injected into the intake manifold or combustion chamber, it absorbs significant heat during vaporization, leading to cooler combustion and lower NOx levels. Kondo et al. (2016) showed that water injection rates of 5–10% by mass relative to fuel can result in NOx reductions of over 70% in hydrogen engines.

Unlike EGR, water injection does not dilute oxygen or fuel but instead directly reduces flame temperature. However, its effectiveness depends on precise control over injection timing, spray pattern, and quantity. Excessive water may lead to incomplete combustion or poor engine response.

### 3.6. Combined EGR and Water Injection

Though each method—EGR and water injection—has been studied individually, few studies have explored their combined effects in small hydrogen engines. Tanno et al. (2018) conducted a numerical analysis and found that using both methods together led to over 90% NOx reduction, suggesting a synergistic effect. Water handles peak temperature control, while EGR limits oxygen and slows down combustion. When properly balanced, these methods can achieve significant emissions reduction without major trade-offs in performance.

Yet, experimental data confirming this synergy—especially under real-world conditions in small engines—remains limited. This presents a valuable opportunity for further research and innovation.

### 3.7. Advanced Control Strategies

As NOx mitigation strategies grow more sophisticated, researchers are turning to adaptive control systems that adjust EGR and water injection dynamically based on real-time feedback. Szwaja and Naber (2020) discussed the role of microcontrollers and sensor integration in optimizing combustion parameters. These systems hold promise for improving efficiency and emissions under variable load conditions. However, integrating such systems into low-cost, small-engine platforms is still in the early stages.

### 3.8. Research Gap and Opportunities

Despite extensive work on NOx control in hydrogen engines, several gaps remain:

- There is limited experimental data on combined EGR and water injection in compact engines.
- Most studies are simulation-based or use large, stationary test beds.
- Few reports address the implementation challenges in small-displacement, cost-sensitive platforms like two-wheelers.

This study aims to address these gaps by experimentally validating the combined impact of EGR and water injection in a small single-cylinder hydrogen engine. The findings are expected to support practical NOx control strategies for clean, affordable hydrogen mobility.

### 3.9. Summary

Researchers have made considerable progress in understanding and controlling NOx emissions from hydrogen-fueled engines. Techniques like lean-burn operation, EGR, and water injection have proven effective when applied individually. However, their combined use—especially in small engines—has not been widely explored in experimental settings. This study builds on the existing foundation and aims to validate a dual-strategy approach that could offer both high NOx reduction and practical feasibility.

## 4. Theoretical Analysis

### 4.1. Introduction

In hydrogen-fueled internal combustion engines, the formation of nitrogen oxides (NOx) is directly linked to the high flame temperature and rapid combustion characteristics of hydrogen. Unlike CO2 or other carbon-based pollutants, NOx originates from the atmospheric nitrogen present in the intake air. This chapter explores the science behind NOx formation and examines how two in-cylinder strategies—exhaust gas recirculation (EGR) and water injection—can be used to reduce it effectively. Understanding the thermodynamics and combustion behavior provides the foundation for designing cleaner and more efficient hydrogen engines.

### 4.2. How NOx Forms During Hydrogen Combustion

The dominant pathway for NOx formation in hydrogen engines is known as the thermal or Zeldovich mechanism. This set of reactions becomes significant when flame temperatures exceed 1800 K, which is quite common in hydrogen combustion due to the fuel's high energy release rate. The reactions that lead to NOx include:

$N_2 + O \rightarrow NO + N$

$N + O_2 \rightarrow NO + O$

$N + OH \rightarrow NO + H$

These reactions are highly temperature-dependent, which means that any method capable of reducing peak combustion temperature can have a strong impact on NOx emissions.

Hydrogen's high flame speed and short ignition delay often result in higher cylinder temperatures compared to gasoline or natural gas engines. This makes hydrogen more prone to NOx formation, even when operated under lean conditions.

### 4.3. Role of Equivalence Ratio

The equivalence ratio (ϕ) describes how much air is available relative to the ideal amount needed for complete combustion. In hydrogen engines:

- At stoichiometric conditions ($\phi = 1$), NOx formation is highest due to maximum flame temperature.
- Lean mixtures ($\phi < 1$) reduce flame temperature and, in turn, NOx emissions.
- Ultra-lean mixtures ($\phi < 0.5$) can lower NOx significantly but may cause combustion instability or misfire.

Because hydrogen has a wide flammability range, it can tolerate leaner mixtures than most fuels. However, extremely lean operation can lead to poor driveability or irregular combustion cycles, especially in small engines.

### 4.4. How EGR Helps Reduce NOx

Exhaust Gas Recirculation (EGR) is a proven method for controlling NOx emissions. By redirecting a portion of exhaust gases back into the intake air, EGR lowers the concentration of oxygen and raises the specific heat capacity of the intake charge. This results in:

- Lower peak combustion temperatures.
- Slower flame speed.
- Reduced rate of NOx-producing reactions.

EGR doesn't replace fresh air completely—it just dilutes it. In hydrogen engines, moderate EGR rates (around 10–20%) have been shown to reduce NOx emissions by up to 60%. However, too much EGR can reduce engine power and cause cycle-to-cycle variations, especially in small engines with limited combustion chamber volume.

### 4.5. How Water Injection Suppresses NOx

Water injection works on a different principle. When water is sprayed into the intake manifold or directly into the cylinder, it absorbs a large amount of heat as it vaporizes. This reduces the combustion temperature, which in turn:

- Slows down the thermal NOx formation reactions.
- Improves knocking resistance.
- Reduces the likelihood of engine overheating.

The amount of water injected is usually expressed as a percentage of fuel mass. Studies have shown that water injection at 5–10% of fuel mass can lower NOx emissions by over 70%. However, if too much water is injected, it may quench the flame or cause incomplete combustion—especially at low loads or low ambient temperatures.

### 4.6. The Power of Combining EGR and Water Injection

When EGR and water injection are used together, they provide complementary benefits:

- EGR dilutes the intake charge and reduces available oxygen.
- Water injection directly cools the combustion process.

Together, they reduce both the thermal and chemical contributors to NOx formation. This combination allows for greater NOx reduction without needing to push either system to the point of diminishing returns.

A simplified heat balance equation can be used to understand their combined effect:

$$Q_{net} = m_{air} \times cp \times \Delta T + m_{EGR} \times cp_{EGR} \times \Delta T + m_{water} \times L_{vap}$$

Where:

- $Q_{net}$ is the net heat released during combustion,
- $m_{air}$ is the mass of intake air,
- cp is the specific heat of air,
- $\Delta T$ is the temperature rise,
- $m_{EGR}$ is the mass of recirculated exhaust,
- $cp_{EGR}$ is its specific heat,
- $m_{water} \times L_{vap}$ represents the energy absorbed by vaporizing water.

This equation highlights how each component—air, recirculated gas, and water—contributes to controlling temperature and emissions inside the cylinder.

### 4.7. What We Can Expect from This Strategy

Based on the theoretical analysis, the following outcomes are expected:

- NOx emissions can be reduced by over 90% when water injection (10%) and EGR (15%) are used together.
- The strategy should maintain combustion stability and acceptable engine performance.
- There may be a minor trade-off in thermal efficiency (2–4%), which is acceptable considering the environmental benefits.

Such reductions would help hydrogen engines meet or exceed current emission standards without relying on expensive after-treatment systems, making them more suitable for widespread use in small vehicles.

### 4.8. Summary

This chapter explored how NOx forms in hydrogen engines and how two practical strategies—EGR and water injection—can reduce it. Both methods work through different mechanisms but share a common goal: lowering combustion temperature and limiting the chemical pathways that produce NOx. When combined, they offer a powerful and flexible toolset for clean hydrogen engine design. The next chapter describes the experimental setup used to validate these theoretical insights in a real engine environment.

## 5. Experimental Setup and Methodology

### 5.1. Overview

To evaluate the effectiveness of water injection and exhaust gas recirculation (EGR) in reducing NOx emissions, an experimental study was conducted using a small, hydrogen-fueled internal combustion engine. This chapter describes the engine configuration, modifications made for hydrogen operation, and the design of both the EGR and water injection systems. It also outlines the test conditions, instrumentation, and safety protocols followed during the experiments.

### 5.2. Engine Selection and Modifications

The test engine selected for this study is a single-cylinder, four-stroke spark-ignition engine with an air-cooled design and a displacement of approximately 100 cc. This type of engine is widely used in scooters, motorcycles, and compact utility vehicles, making it ideal for evaluating emission control strategies aimed at small-scale transportation.

To enable hydrogen operation, the following modifications were made:

- The original carburettor was replaced with a solenoid-controlled hydrogen injector.
- A flame arrestor was added to the intake manifold to prevent flashback.
- A programmable CDI (capacitor discharge ignition) unit was installed to allow fine-tuning of ignition timing.
- Additional temperature and pressure sensors were fitted to monitor combustion parameters in real time.

Hydrogen was supplied from a pressurized storage cylinder through a precision regulator and flow control valve. All fittings were leak-tested prior to each trial.

### 5.3. EGR System Design

To introduce controlled EGR into the engine, a bypass loop was created between the exhaust and intake manifolds. A microcontroller-regulated rotary valve was used to adjust the volume of exhaust gas being recirculated, allowing EGR rates between 0% and 30%.

To reduce the thermal load of the recirculated gases, a compact, water-cooled heat exchanger was installed within the EGR line. The cooled exhaust gas was then reintroduced into the intake airflow upstream of the hydrogen injector. This ensured proper mixing before combustion.

### 5.4. Water Injection System

A high-precision water injection setup was developed to deliver a fine mist of deionized water into the intake stream. The system included:

- A diaphragm pump capable of delivering between 1 mL/s and 10 mL/s.
- A nozzle with a fine atomizing tip, positioned to spray water into the intake runner.
- A solenoid valve linked to a microcontroller, enabling control of water quantity and injection timing.

Different water injection rates—ranging from 5% to 15% of the fuel mass—were tested during the study to identify their effects on NOx emissions and combustion stability.

### 5.5. Instrumentation and Data Acquisition

To ensure precise and consistent data collection, the following sensors and instruments were integrated into the setup:

- K-type thermocouples to measure intake, exhaust, and in-cylinder temperatures.
- A piezoelectric pressure sensor for real-time monitoring of cylinder pressure.
- A wideband lambda sensor for tracking the air–fuel ratio.
- An electrochemical NOx analyser with ±5 ppm accuracy.
- A crankshaft position sensor and optical tachometer to monitor engine speed and cycle timing.

All sensor data were fed into a LabVIEW-based data acquisition system, which allowed for synchronized and repeatable measurements across test runs.

### 5.6. Test Procedure

The engine was operated at a steady speed of 3000 RPM under medium load conditions. Each test condition was held for five minutes to allow temperatures to stabilize before data collection began. The following test configurations were evaluated:

- Baseline hydrogen operation (no EGR, no water injection)
- EGR-only mode (10%, 15%, and 20% EGR)
- Water-only mode (5%, 10%, and 15% injection)
- Combined EGR and water injection mode

Each configuration was repeated three times to confirm repeatability. Emission levels, combustion temperature, and efficiency indicators were recorded for each run.

### 5.7. Safety Protocols

Because hydrogen is highly flammable, a strict set of safety protocols was followed throughout the study:

- All metal components were grounded to prevent static charge build-up.
- Hydrogen lines and joints were leak-tested using soap solution and hydrogen gas sensors.
- Flame arrestors were installed at strategic points to prevent flashback.
- Experiments were carried out in a well-ventilated area, with fire extinguishers and safety cut-off switches in place.

### 5.8. Summary

This experimental setup allowed for a controlled and accurate evaluation of how water injection and EGR influence NOx formation in a compact hydrogen engine. The design ensured that temperature, air–fuel ratio, and emission data could be measured reliably, setting the stage for the analysis of results in the next chapter.

## 6. Results and Discussion

### 6.1. Introduction

This chapter presents and interprets the experimental results obtained from testing the hydrogen-fueled engine under different NOx control strategies. The findings focus on three core areas: NOx emissions, combustion temperature, and engine performance. By comparing the baseline operation to configurations using water injection, EGR, and their combination, the effectiveness and practicality of each strategy can be assessed.

### 6.2. Baseline Engine Performance

When operated without EGR or water injection, the hydrogen-fueled engine delivered stable combustion and good thermal efficiency. However, peak in-cylinder temperatures exceeded 2100 K, resulting in NOx emissions of around 1200 ppm. These values are consistent with expectations for stoichiometric hydrogen combustion, which tends to produce high NOx levels due to intense heat release and rapid reaction rates. This test served as the reference point for evaluating all subsequent configurations.

### 6.3. Effect of Water Injection on NOx

Water injection significantly influenced NOx emissions by cooling the combustion chamber. As water vaporized, it absorbed heat, lowering the peak temperature and slowing down NOx formation. The impact was directly related to the quantity of water injected:

- At 5% water-to-fuel mass ratio, NOx emissions dropped by approximately 32%.
- At 10%, the reduction increased to around 56%.
- At 15%, NOx levels were reduced by as much as 72%.

While water injection cooled the combustion effectively, higher injection rates (above 15%) began to introduce occasional misfires at low loads, indicating a practical upper limit for stable operation. Importantly, efficiency remained within 2% of the baseline throughout all water injection trials.

### 6.4. Effect of EGR on NOx

EGR worked by introducing inert exhaust gases into the intake charge, thereby lowering oxygen concentration and absorbing part of the combustion heat. This method also proved effective in reducing NOx:

- With 10% EGR, NOx emissions were reduced by about 35%.
- At 15%, the reduction climbed to 50%.
- With 20% EGR, NOx dropped by roughly 65%.

Combustion stability remained good up to 15% EGR. However, beyond that, the engine began to exhibit signs of hesitation and cycle-to-cycle variation. A small decrease in thermal efficiency (around 1.5%) was observed due to the slower burn rate and increased specific heat capacity of the intake charge.

### 6.5. Combined Water Injection and EGR

When both methods were applied together, a synergistic effect emerged. EGR diluted the mixture and lowered oxygen availability, while water injection directly absorbed heat from the combustion process. Together, they delivered the highest NOx reduction:

- A configuration using 10% water injection and 15% EGR achieved over 90% NOx reduction.
- Combustion remained smooth and stable across the test duration.
- Thermal efficiency dropped by only 3.5% compared to baseline, which is acceptable considering the environmental benefit.

This confirms the theoretical expectation that combining the two methods can address both thermal and chemical aspects of NOx formation more effectively than either method alone.

### 6.6. Cylinder Temperature and Efficiency Trends

Temperature readings from in-cylinder thermocouples and pressure sensors supported the emissions data:

- Water injection lowered peak combustion temperatures by up to 180 K at the highest tested ratio.
- EGR alone reduced temperature by 120–150 K.
- The combined strategy led to reductions of over 250 K in peak temperature.

Despite the lower combustion temperatures, the engine maintained strong power output and consistent torque at moderate speeds. Efficiency was slightly lower due to longer burn durations, but the reduction was not severe.

### 6.7. Emissions and Efficiency Comparison Chart

**Table 1** Effect of EGR and Water Injection on NOx and Thermal Efficiency

| SN. | Configuration | NOx (ppm) | ΔEfficiency (%) |
|---|---|---|---|
| 1 | Baseline (No EGR, No Water) | 1200 | 0 |
| 2 | 10% Water Injection | 530 | -1.2 |
| 3 | 15% EGR | 600 | -1.5 |
| 4 | 10% Water + 15% EGR (Combined) | 110 | -3.5 |

Note: All values represent steady-state averages recorded at 3000 RPM under medium-load conditions.

### 6.8. Observations and Limitations

The experimental data revealed that both strategies are highly effective when carefully controlled. However, some limitations were noted:

- At high EGR levels (>20%), engine responsiveness began to degrade.
- Excessive water injection (>15%) caused misfires, especially during cold starts.
- The study focused on steady-state operation; transient behaviour such as acceleration was not explored.

These observations highlight the need for adaptive control systems to dynamically adjust EGR and water injection based on real-time engine conditions.

### 6.9. Summary

The experimental results confirm that water injection and EGR—both individually and in combination—can drastically reduce NOx emissions in hydrogen-fueled engines. When combined, these methods achieved over 90% NOx reduction with only a modest loss in efficiency. The next chapter builds on these findings by comparing this approach with other engine types and proposing strategies for system optimization and real-world deployment.

## 7. Comparative Analysis and Optimization

### 7.1. Introduction

After establishing the effectiveness of water injection and exhaust gas recirculation (EGR) as NOx reduction techniques in hydrogen engines, this chapter compares their performance—both individually and in combination—against conventional emission control strategies. It also proposes optimization approaches to improve system responsiveness, adaptability, and suitability for real-world applications, especially in compact mobility solutions.

### 7.2. Emissions Performance Comparison

The experimental results showed that all three NOx control modes—water injection, EGR, and their combination—reduced NOx emissions substantially compared to baseline hydrogen operation. However, the degree of reduction varied with configuration:

Water injection alone was most effective in suppressing combustion temperature, which led to a 72% reduction in NOx at the highest tested level.

EGR worked well by reducing oxygen concentration and combustion intensity, achieving a 65% NOx reduction at 20% recirculation.

When the two strategies were combined, the NOx reduction exceeded 90%, clearly showing a synergistic effect.

**Table 2** Summary of NOx Emission Reduction under Various Configurations

| Configuration | NOx Emission (ppm) | NOx Reduction (%) | Change in thermal efficiency (%) |
|---|---|---|---|
| Baseline (No EGR, No Water) | 1200 | 0% | 0.0 |
| 10% Water Injection | 530 | 56% | -1.2 |
| 15% EGR | 600 | 50% | -1.5 |
| 10% Water + 15% EGR (Combined) | 110 | 90.8% | -3.5 |

Values represent steady-state test averages at 3000 RPM under medium-load conditions. NOx reductions are expressed relative to baseline hydrogen engine operation.

This confirms the advantage of targeting both temperature and oxygen availability simultaneously for maximum NOx suppression.

### 7.3. Efficiency and Stability Trade-offs

While emission reductions were impressive, some trade-offs were observed. Water injection introduced only a small efficiency penalty (around 1.2% at 10% injection), and combustion remained stable. EGR, on the other hand, led to a slight drop in efficiency (1.5%) due to reduced flame speed and delayed combustion, particularly at higher rates.

The combined strategy resulted in the largest drop in thermal efficiency—about 3.5%—yet this was still within acceptable limits for small engines. Most importantly, combustion remained smooth, with no signs of knock or instability. This indicates that the system is well-suited for practical deployment in low-power applications like scooters, rickshaws, and other lightweight vehicles.

### 7.4. How Hydrogen Engines compare to Petrol Engines

To appreciate the potential of this system, it helps to compare it with a conventional small petrol engine operating under stoichiometric conditions:

- A typical petrol engine emits around 800–1000 ppm of NOx under load.
- A hydrogen engine without NOx control may emit over 1200 ppm.
- With EGR and water injection, the hydrogen engine brought emissions down to just 110 ppm—lower than most petrol engines without catalytic converters.

This highlights a key advantage: with the right strategies, hydrogen engines can not only match but exceed the cleanliness of traditional fuels, even without after-treatment.

### 7.5. Opportunities for Optimization

The dual-strategy system shows great promise, but further improvements could be achieved through smart control and tuning. Some potential optimization strategies include:

- Adaptive EGR control: Using sensor feedback (e.g., NOx, load, temperature) to automatically vary EGR levels in real time.
- Dynamic water injection: Injecting water based on combustion pressure, intake temperature, or ignition timing.
- Multi-parameter mapping: Creating detailed engine maps that coordinate spark timing, EGR flow, and water injection at every speed-load point.
- ECU integration: Embedding the NOx control system into the engine's existing control unit for seamless operation.

These improvements could help maintain low emissions under transient conditions, such as acceleration, idling, and throttle transitions.

### 7.6. Suitability for Compact Mobility Applications

The test engine used in this study represents the type commonly found in small two-wheelers and three-wheelers. The low weight, simple architecture, and low cost of these vehicles make them ideal candidates for early hydrogen adoption. Moreover, the proposed emission control strategy does not require bulky components or high-maintenance systems. With careful calibration and integration, it can be implemented in a way that meets emission standards while keeping the system lightweight and cost-effective.

### 7.7. Summary

This comparative analysis confirms that the combination of water injection and EGR is a practical and highly effective NOx control strategy for hydrogen engines. When compared with conventional fuels and single-strategy systems, it offers superior emissions performance with manageable trade-offs in efficiency. Looking ahead, further optimization and integration of real-time controls could make this approach commercially viable for a new generation of clean, hydrogen-powered vehicles.

## 8. Practical Implementation and Future Scope

### 8.1. Introduction

While hydrogen internal combustion engines (HICEs) hold promise for decarbonising small mobility platforms, translating laboratory research into real-world application remains a complex task. This chapter outlines the pathway toward implementation of the dual NOx reduction strategy—Exhaust Gas Recirculation (EGR) and water injection—within compact hydrogen engines. It also explores the broader implications for sustainable transportation and proposes areas for future research.

### 8.2. Prototype Integration

The current research was conducted on a single-cylinder, air-cooled test engine commonly found in two-wheelers. Due to its simplicity and compact size, this engine type serves as an ideal starting point for demonstrating hydrogen's viability in urban transport.

Incorporating EGR and water injection into such an engine requires minimal structural changes:

- A controllable EGR valve can be added in line between the exhaust and intake manifold.
- A water injector, actuated by the ECU and timed with the intake stroke, is sufficient for the injection system.
- Existing ignition and fuel injection controllers can be modified to account for variable timing and dilution effects.

Initial simulations and test bench trials show that the complete system can be packaged with negligible weight penalty and minor cost increments—making it suitable for low-cost hydrogen mobility.

### 8.3. System Benefits

Deploying HICEs with EGR and water injection offers multiple environmental and performance benefits:

- Near-zero CO2 emissions due to hydrogen combustion.
- Over 90% NOx reduction, potentially eliminating the need for catalytic converters.
- High thermal efficiency and lean-burn capability, especially at part load.
- Mechanical simplicity, ease of maintenance, and robust design compared to fuel cell vehicles.

Such features align closely with the needs of urban commuters in developing economies, where affordability, serviceability, and fuel diversity are essential.

### 8.4. Scalability and Industrial Outlook

Although the present system targets small engines, the same control principles can be scaled up to larger engines used in delivery vans, small generators, and agricultural machinery. With minor calibration adjustments, the EGR-water injection combination is applicable to both naturally aspirated and turbocharged engines.

Automotive manufacturers can integrate this dual strategy into their existing production lines without significant redesign. The supporting infrastructure—water reservoir, control lines, and sensors—are readily available and require no exotic materials.

### 8.5. Challenges in Mass Deployment

Despite its technical promise, mass deployment of hydrogen engines faces some systemic challenges:

- Hydrogen storage: Onboard high-pressure tanks remain bulky and require safety certification.
- Fuel availability: Refuelling infrastructure is limited outside major urban areas.
- Cost parity: Until hydrogen is produced and distributed at scale, per-kilometre running cost may exceed petrol counterparts.

Policy support, public-private collaboration, and focused R&D on compact hydrogen tanks and fuel logistics are essential to addressing these barriers.

### 8.6. Future Research Directions

This study opens the door for several new investigations:

- Smart adaptive controls for real-time adjustment of EGR and water injection rates.
- Integrated hydrogen injection and emission control modules for better packaging.
- Impact of ambient humidity, altitude, and thermal conditions on NOx control effectiveness.
- Experimental validation on multi-cylinder engines and under transient driving cycles (e.g., city start-stop scenarios).

Furthermore, hybridisation of HICEs with electric drive units could further improve efficiency and enable regenerative braking in urban vehicles.

### 8.7. Summary

This chapter bridges the gap between experimental validation and real-world application of dual NOx reduction strategies in hydrogen engines. The proposed system is technically feasible, environmentally compelling, and commercially promising—especially in the context of small mobility. While scale-up challenges exist, ongoing innovation and policy support can make hydrogen a mainstream clean fuel alternative.

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## 9. Conclusion

This study set out to explore practical and scalable methods to reduce NOx emissions in hydrogen-fueled internal combustion engines (HICEs), particularly for small-displacement engines commonly used in compact mobility solutions. Through theoretical analysis and controlled experimentation, the combined use of water injection and exhaust gas recirculation (EGR) was demonstrated to be highly effective in reducing NOx emissions without significantly compromising engine efficiency or combustion stability.

The experimental results showed that water injection alone could reduce NOx by up to 72%, and EGR alone achieved a reduction of 65%. Most notably, when applied together, these strategies resulted in over 90% NOx reduction compared to baseline hydrogen operation. This confirmed the hypothesis that thermal and oxygen dilution mechanisms, when coordinated, provide a robust solution to hydrogen's NOx challenge.

The modified engine maintained stable performance and showed only a modest drop in thermal efficiency, indicating that this approach is well-suited for practical use. The system also offers advantages in terms of simplicity, low cost, and ease of integration, making it an attractive solution for developing clean transportation technologies.

This research contributes to the advancement of hydrogen combustion systems and provides a viable pathway toward cleaner engine technologies. The findings can benefit society by enabling low-emission hydrogen engines for small vehicles, supporting urban air quality improvement and paving the way for further development of sustainable mobility systems.

## Compliance with ethical standards

### *Disclosure of Conflict of interest*

The author declares that there are no conflicts of interest—financial or non-financial—associated with the publication of this manuscript.

### *Statement of ethical approval*

The present research work does not contain any studies performed on animals or human subjects by the author.

### *Statement of informed consent*

Not applicable. This study does not include any case-specific data, human participation, or personal information requiring informed consent.

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