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PAPER

The effects of a low-pressure port fuel injection on the performance characteristics of a hydrogen–diesel dual-fuel compression ignition engine

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Abstract

Hydrogen has gained increasing attention as a supplementary fuel for internal combustion engines due to its high energy content and carbon-free combustion characteristics. This study experimentally investigates the performance and emission behavior of a hydrogen–diesel dual-fuel compression ignition engine under varying hydrogen injection pressures. A single-cylinder, four-stroke, direct-injection Yanmar L48N diesel engine was modified to operate in hydrogen–diesel bi-fuel mode using a port fuel injection system for hydrogen delivery. Experiments were conducted in hydrogen–diesel dual-fuel mode at hydrogen injection pressures of 0.5, 1.0, and 1.5 bar over an engine speed range of 1800–3600 rpm under approximately 50% constant load conditions The results indicate that hydrogen enrichment improves engine performance parameters, including brake power, torque, brake mean effective pressure, and brake specific fuel consumption, particularly at higher hydrogen pressures. The highest brake thermal efficiency of approximately 13% was achieved at a hydrogen pressure of 1.5 bar. In terms of emissions, hydrogen addition significantly reduced carbon dioxide (CO_2) emissions due to its carbon-free nature. However, increases in nitrogen oxide (NO_x) emissions were observed, especially at higher hydrogen pressures, attributed to elevated in-cylinder combustion temperatures. Unburned hydrocarbon and carbon monoxide (CO) emissions increased under certain operating conditions, primarily due to non-optimized hydrogen injection timing. Overall, the findings demonstrate that hydrogen–diesel dual-fuel operation can enhance engine performance and reduce carbon-related emissions. However, precise control of hydrogen injection parameters is essential to mitigate NO_x formation and incomplete combustion effects.

1. Introduction

The transportation and power generation sectors remain heavily dependent on fossil fuels, particularly diesel, contributing significantly to greenhouse gas emissions and air pollution. Despite growing interest in electrification, internal combustion engines (ICEs) are expected to continue playing a critical role in global energy systems due to limitations associated with battery cost, resource availability, and infrastructure readiness (Moriarty and Honnery 2019, Jayakumar *et al* 2022). Consequently, improving the environmental performance of conventional engines through alternative and low-carbon fuels has become a key research priority.

Hydrogen has emerged as a promising energy carrier for sustainable transportation owing to its high lower heating value, rapid flame propagation, and zero carbon content during combustion (Acar and Dincer 2020, Akal *et al* 2020). When applied in ICEs, hydrogen offers the potential to reduce carbon-based emissions while maintaining acceptable engine performance. However, hydrogen cannot be directly utilized in conventional compression ignition (CI) engines because of its high auto-ignition temperature and low cetane number. As a result, hydrogen is commonly introduced in dual-fuel mode, where diesel is used as a pilot fuel to initiate combustion (Ikegami *et al* 1982, Hosseini *et al* 2023).

Extensive experimental and numerical studies have investigated hydrogen–diesel dual-fuel combustion under various operating conditions. Reported results indicate that hydrogen enrichment can improve brake thermal efficiency (BTE) and reduce brake specific fuel consumption (BSFC) due to enhanced combustion characteristics and reduced ignition delay (Castro *et al* 2019, Seelam *et al* 2022; Gültekin & Ciniviz, 2023a). Additionally, hydrogen addition consistently reduces carbon dioxide (CO_2) emissions, reflecting its carbon-free nature (Acar and Dincer 2020, Bakar *et al* 2024).

These advantages position hydrogen–diesel dual-fuel operation as a viable transitional solution toward low-carbon engine technologies.

Hydrogen delivery strategies in CI engines are generally classified into direct injection (DI) and port fuel injection (PFI). DI hydrogen systems have demonstrated superior control over mixture formation, reduced backfire tendency, and improved volumetric efficiency (Furuhama and Fukuma 1986, Yip *et al* 2019, Babayev *et al* 2022). However, the requirement for high-pressure injection systems capable of overcoming in-cylinder pressure significantly increases system complexity and cost (Bayramoğlu and Yılmaz 2021, Park *et al* 2022). In contrast, PFI hydrogen systems are simpler, cost-effective, and more suitable for retrofitting existing diesel engines, making them the preferred configuration in many experimental studies (Castro *et al* 2019, Khalid *et al* 2024).

Despite extensive research, emission behavior in hydrogen–diesel dual-fuel engines remains highly inconsistent. While reductions in CO_2 emissions are consistently reported, conflicting trends are observed for carbon monoxide (CO), unburned hydrocarbons (UHC), and nitrogen oxides (NO_x). Several studies report increased NO_x emissions with hydrogen enrichment due to elevated in-cylinder temperatures associated with hydrogen's high flame speed and adiabatic flame temperature (Lamas and Rodriguez 2019, Kumar *et al* 2022, Bakar *et al* 2024). Conversely, stable or reduced NO_x levels have been observed under lean operating conditions or with appropriate combustion control strategies (Dhyani and Subramanian 2019, Hosseini *et al* 2023). Similarly, contradictory trends in CO and UHC emissions have been reported, often attributed to incomplete combustion, inadequate pilot fuel quantity, and non-optimized hydrogen injection parameters (Khatri and Khatri 2020, Gültekin and Ciniviz, 2023b).

A key limitation identified in the existing literature is the limited systematic investigation of hydrogen injection pressure, particularly under PFI configurations. Most studies emphasize hydrogen substitution ratio, injection timing, or pilot fuel strategies (Tripathi *et al* 2019, Kumar *et al* 2022, Park *et al* 2022), while hydrogen injection pressure an important parameter influencing mixture formation, combustion stability, and emission formation has received comparatively less experimental attention (Menaa *et al* 2019). Furthermore, many investigations are conducted at fixed engine speeds or variable load conditions, restricting the ability to isolate the influence of injection pressure across a wide operating range.

In response to these gaps, the present study experimentally investigates the effect of hydrogen injection pressure in a PFI hydrogen–diesel dual-fuel CI engine operating under constant load over a wide range of engine speeds. The study aims to evaluate engine performance parameters and exhaust emissions at different hydrogen injection pressures, providing insight into the trade-offs between efficiency improvement and emission formation. The findings contribute to a clearer understanding of hydrogen injection pressure effects and support the optimization of hydrogen-assisted diesel combustion for improved efficiency and environmental performance.

2. Literature review

2.1. Hydrogen as a sustainable fuel for ICEs

Hydrogen has attracted significant attention as an alternative energy carrier for ICEs due to its high lower heating value, rapid flame propagation, and zero carbon emissions at the point of use. From a sustainability perspective, hydrogen offers strong potential for mitigating greenhouse gas emissions in the transportation sector, particularly when produced from low-carbon pathways (Moriarty and Honnery 2019, Acar and Dincer 2020). Several studies have highlighted hydrogen's role as a transitional fuel that can complement existing engine technologies while supporting decarbonization goals (Jayakumar *et al* 2022, Hosseini *et al* 2023).

Despite these advantages, hydrogen presents combustion-related challenges, including high auto-ignition temperature, low density, and increased propensity for abnormal combustion under improper operating conditions. These characteristics restrict the direct application of hydrogen in CI engines, necessitating its use in dual-fuel configurations where a high-cetane fuel such as diesel initiates combustion (Ikegami *et al* 1982, Akal *et al* 2020).

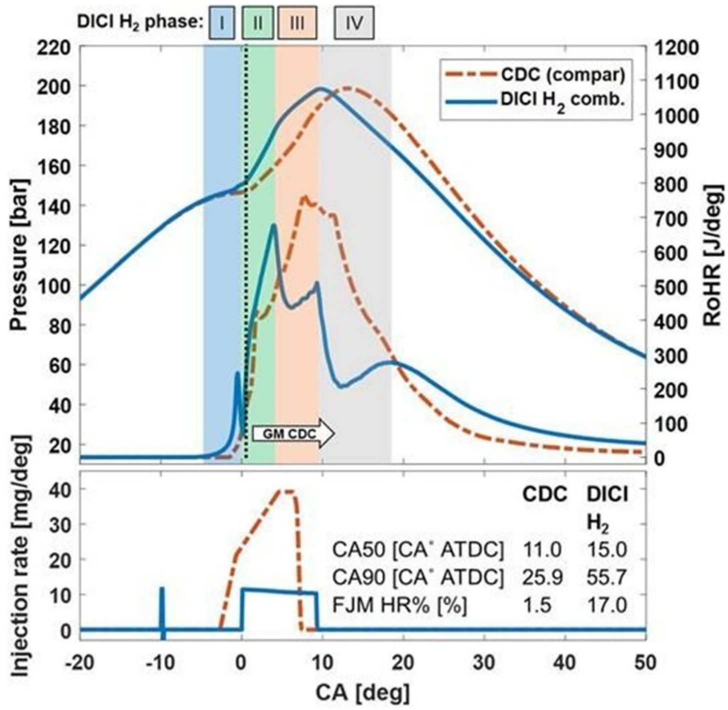

Figure 1. The injection rate, heat release rate, pressure traces, and several combustion cycle metrics for DICI H2 cases. Reproduced from Babayev *et al* (2022).

2.2. Hydrogen–diesel dual-fuel combustion concepts

Hydrogen–diesel dual-fuel operation has been extensively investigated as a strategy to combine the high efficiency of CI engines with the low-carbon benefits of hydrogen. In this configuration, diesel is injected as a pilot fuel to initiate ignition, while hydrogen contributes to the main energy release. Experimental and numerical studies consistently report improvements in combustion efficiency and reductions in carbon-related emissions compared to diesel-only operation (Castro *et al* 2019, Seelam *et al* 2022; and ltekin & Ciniviz 2023a).

However, reported outcomes vary widely depending on hydrogen delivery method, engine operating conditions, and injection parameters. Boretti (2019) emphasized that dual-fuel engines exhibit complex combustion behavior, where performance and emissions are highly sensitive to fuel interaction and combustion phasing. This sensitivity partly explains the contradictory trends observed across the literature, particularly with respect to nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UHC). Figure 1 illustrates the general classification of hydrogen injection strategies for CI engines, highlighting key advantages and limitations of DI and PFI configurations.

2.3. Hydrogen injection strategies: DI versus PFI

Hydrogen delivery strategies in CI engines are broadly classified into DI and PFI. DI hydrogen systems provide superior control over mixture formation and minimize backfire risks by avoiding hydrogen–air premixing in the intake manifold (Furuhama and Fukuma 1986, Yip *et al* 2019). Advanced DI configurations, including hydrogen DI CI (H2DDI), have demonstrated promising performance and emission characteristics in both experimental and computational studies (Liu *et al* 2021, Babayev *et al* 2022).

Nevertheless, DI hydrogen systems require high-pressure injection equipment capable of overcoming in-cylinder pressure, which significantly increases system complexity, cost, and safety requirements (Bayramoğlu and Yılmaz 2021, Park *et al* 2022). As a result, PFI hydrogen systems remain the most widely adopted configuration in experimental investigations, particularly for retrofit applications (Castro *et al* 2019, Khalid *et al* 2024).

PFI systems allow hydrogen to mix with intake air prior to combustion, simplifying system design but introducing challenges related to volumetric efficiency, backfire, and mixture inhomogeneity. Khalid *et al* (2024) highlighted that improper hydrogen injection control under PFI configurations can exacerbate abnormal combustion and emission formation, reinforcing the importance of injection parameter optimization.

2.4. Performance characteristics of hydrogen–diesel dual-fuel engines

Numerous studies report that hydrogen enrichment improves BTE and reduces BSFC, particularly at moderate hydrogen energy fractions (Seelam *et al* 2022, Gültekin and Ciniviz, 2023b). These improvements are primarily attributed to hydrogen's high flame speed and enhanced combustion efficiency, which reduce ignition delay and improve heat release characteristics.

However, contradictory findings have also been reported. Khatri and Khatri (2020) observed marginal performance improvements under certain operating conditions, while Pham *et al* (2022) noted that excessive hydrogen supply can degrade performance due to combustion instability and reduced volumetric efficiency. These inconsistencies indicate that hydrogen addition alone does not guarantee performance enhancement without proper control of injection parameters.

2.5. Emission characteristics and contradictions in the literature

2.5.1. Carbon-based emissions

Reductions in carbon dioxide (CO_2) emissions are consistently reported in hydrogen–diesel dual-fuel studies due to hydrogen's carbon-free nature (Acar and Dincer 2020, Hosseini *et al* 2023). However, trends for CO and UHC emissions are inconsistent. Several investigations report reduced CO and UHC emissions due to improved oxidation and enhanced combustion (Castro *et al* 2019, Seelam *et al* 2022), while others report increases, particularly at low engine speeds or under non-optimized injection conditions (Khatri and Khatri 2020, Gültekin and Ciniviz, 2023b).

These increases are commonly attributed to incomplete combustion, insufficient pilot fuel quantity, and inadequate hydrogen–air mixing, highlighting the sensitivity of emission outcomes to hydrogen delivery parameters.

2.5.2. Nitrogen oxides emissions

NO_x emissions represent the most debated outcome in hydrogen–diesel dual-fuel combustion. Many studies report increased NO_x formation due to elevated in-cylinder temperatures associated with hydrogen's high adiabatic flame temperature (Lamas and Rodriguez 2019, Kumar *et al* 2022, Bakar *et al* 2024). Conversely, reductions or stable NO_x levels have been observed under lean operating conditions or when mitigation strategies such as exhaust gas recirculation, water injection, or optimized injection timing are employed (Dhyani and Subramanian 2019, Hosseini *et al* 2023).

These contradictory findings suggest that NO_x formation is governed primarily by combustion control strategies rather than hydrogen addition alone.

2.6. Research gaps and motivation of the present study

Although extensive research has been conducted on hydrogen–diesel dual-fuel engines, systematic investigation of hydrogen injection pressure, particularly under PFI configurations, remains limited. Most studies focus on hydrogen substitution ratio, injection timing, or pilot fuel strategies (Tripathi *et al* 2019, Kumar *et al* 2022, Park *et al* 2022), while injection pressure which directly influences mixture formation, combustion stability, and emission formation has received comparatively little experimental attention (Menaa *et al* 2019).

Furthermore, many studies are conducted at fixed engine speeds or variable load conditions, restricting the ability to isolate the effects of injection pressure across a wide operating range. The inconsistencies reported in emission trends across the literature further underscore the need for controlled experimental investigations that isolate individual hydrogen supply parameters.

Accordingly, the present study addresses these gaps by experimentally evaluating the influence of hydrogen injection pressure under a PFI configuration on the performance and emission characteristics of a hydrogen–diesel dual-fuel CI engine operating under constant load conditions over a wide speed range.

3. Methodology

3.1. Engine test setup

The experimental investigation was conducted using a single-cylinder, four-stroke, air-cooled, direct-injection CI diesel engine (Yanmar L48N). The engine was modified to operate in hydrogen–diesel dual-fuel mode, where diesel served as the pilot fuel and hydrogen was supplied as the supplementary fuel. This configuration is widely adopted in hydrogen–diesel research due to its simplicity, safety, and feasibility for retrofitting conventional diesel engines (Castro *et al* 2019, Khalid *et al* 2024).

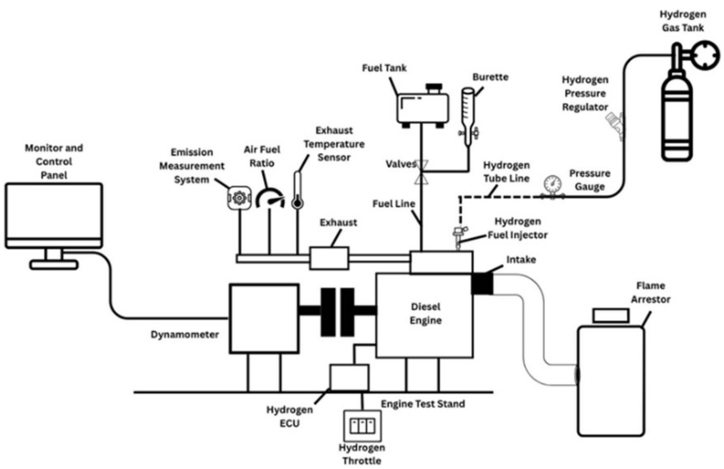

Figure 2. Schematic diagram of the experimental setup for the hydrogen–diesel dual-fuel compression ignition engine.

Table 1. Measurement instrument specifications.

Parameter	Instrument	Measurement range	Accuracy	Resolution
Engine speed	Digital tachometer	0–6000 rpm	±10 rpm	1 rpm
Torque	Eddy current dynamometer	0–20 Nm	±0.1 Nm	0.01 Nm
Brake power	Calculated (from torque & speed)	0–5 kW	±2%	0.01 kW
Fuel consumption	Burette & stopwatch	—	±0.5%	—
CO	Gas analyzer	0%–10% vol	±1%	0.01%
CO_2	Gas analyzer	0%–20% vol	±1%	0.01%
NO_x	Gas analyzer	0–5000 ppm	±2%	1 ppm
UHC	Gas analyzer	0–10 000 ppm	±2%	1 ppm

Hydrogen was supplied through a PFI system installed at the intake manifold, upstream of the intake valve. The selection of a PFI configuration was motivated by its lower system complexity and cost compared to direct hydrogen injection systems, which require high-pressure injectors capable of overcoming in-cylinder pressure (Yip *et al* 2019, Bayramoğlu and Yılmaz 2021). A schematic diagram of the experimental setup is shown in figure 2, illustrating the hydrogen supply system, engine configuration, instrumentation, and exhaust gas measurement layout.

The engine was coupled to an eddy current dynamometer to apply load and measure brake power and torque. Engine speed was controlled and monitored using a digital tachometer. Baseline diesel-only operation was first established to ensure stable engine performance and repeatability prior to hydrogen enrichment, following procedures reported in previous hydrogen dual-fuel studies (Seelam *et al* 2022, Gültekin and Ciniviz 2023a).

The specifications of the main instruments, including measurement range, accuracy, and resolution, are summarized in table 1. These values are based on manufacturer specifications and standard calibration data. The selected instruments provide sufficient precision for evaluating performance and emission characteristics under the tested operating conditions.

3.2. Hydrogen supply system and injection parameters

Hydrogen gas was stored in a high-pressure cylinder and supplied to the engine intake through a pressure regulator, flame arrestor, and solenoid valve to ensure safe operation. In the present study, hydrogen supply was controlled using a pressure-regulated PFI system, where injection pressure was set at 0.5, 1.0, and 1.5 bar. It should be noted that hydrogen mass flow rate was not independently controlled or directly measured; instead, it varied as a function of the regulated injection pressure.

The hydrogen injection pressure was monitored using an analog pressure gauge installed upstream of the injector. The hydrogen flow was introduced continuously during engine operation, while diesel injection parameters were kept unchanged to isolate the influence of hydrogen injection pressure. The hydrogen engine test bed and safety components are illustrated in figure 3. Meanwhile, the hydrogen port fuel injection sistem were closely showed on the figure 4.

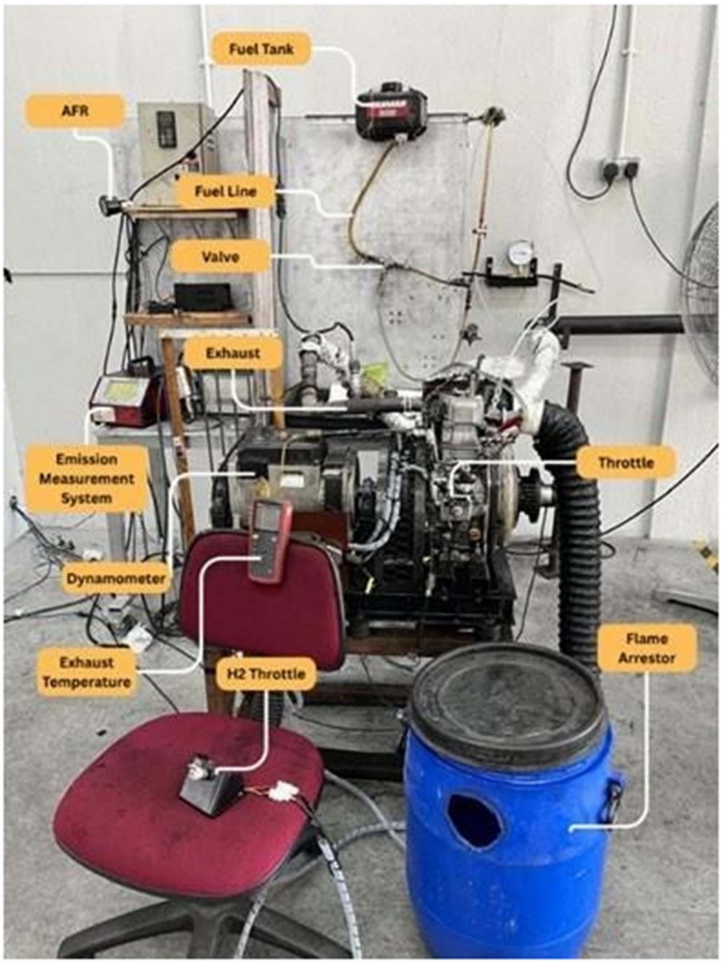

Figure 3. The hydrogen engine test bed and safety components.

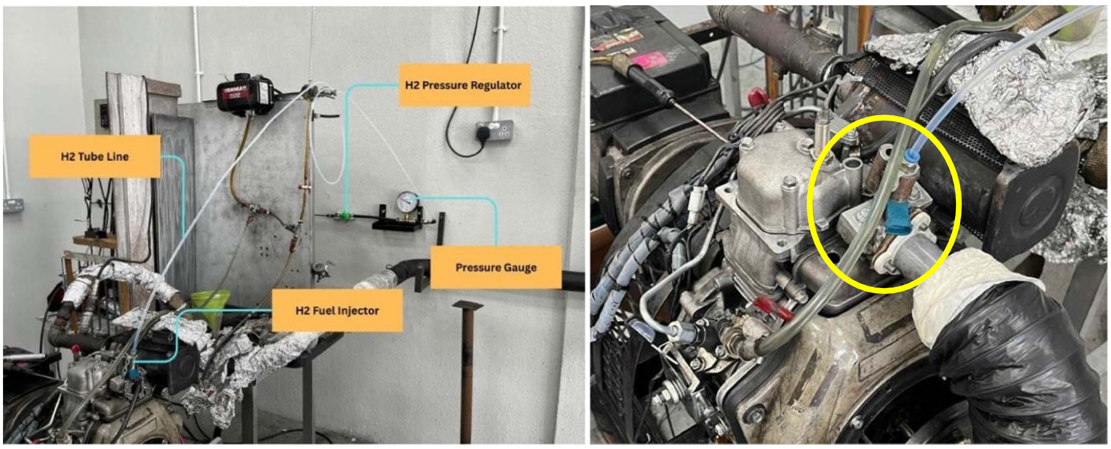

Figure 4. Hydrogen port fuel injection system showing pressure regulation, and injector location.

The error bar graph was presented as shown in figure 5 represent the measurement uncertainty associated with each BSFC value. These error bars indicate the possible range within which the actual value may vary due to experimental or instrument-related uncertainties. This bar graph error are presented to validate the data on this experiment good measurement reliability. Since the error bars are relatively small compared to the overall trend, the results can be considered consistent and reliable. The focus on injection pressure rather than substitution ratio was intended to address a key gap in existing literature, as most prior studies emphasize hydrogen flow rate or energy fraction rather than injection pressure

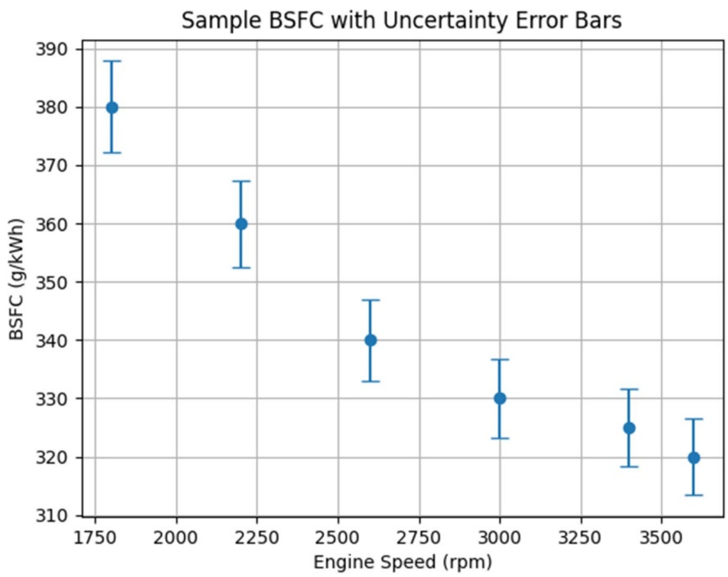

Figure 5. Error bar graph.

effects under PFI configurations (Tripathi *et al* 2019, Kumar *et al* 2022). As the hydrogen injection pressure increased, the volumetric flow rate of hydrogen supplied to the intake manifold also increased due to the higher-pressure differential across the injector.

Consequently, increasing hydrogen injection pressure also increased the hydrogen volumetric flow rate and corresponding hydrogen energy input into the engine. Therefore, the investigated parameter should be interpreted as a coupled pressure–energy input effect rather than an isolated injection pressure effect.

Therefore, the effect of hydrogen injection pressure observed in this study inherently includes the combined influence of both injection pressure and hydrogen mass flow rate (energy input). This approach reflects a practical PFI implementation, where pressure regulation is commonly used as a simple method to vary hydrogen supply. Based on typical flow behavior of low-pressure gaseous injection systems and comparable studies reported in the literature, the hydrogen energy substitution ratio in the present work is estimated to increase progressively with injection pressure, likely within a moderate range (approximately 5%–20% of total fuel energy input).

Although precise mass flow rate and equivalence ratio were not measured, the trends observed in engine performance and emissions are consistent with increased hydrogen energy contribution at higher injection pressures. Future work will focus on direct measurement and control of hydrogen mass flow rate to further isolate the effects of injection pressure from fuel quantity.

3.3. Experimental procedure

All experiments were conducted at constant load conditions, while engine speed was varied from 1800 to 3600 rpm and controlled by adjusting the engine throttle/fuel supply, while the dynamometer continuously regulated the applied load to maintain constant loading conditions. The load was monitored via dynamometer readings to ensure minimal fluctuation throughout each test. For each operating condition, measurements were first recorded under diesel-only operation, followed by hydrogen–diesel dual-fuel operation at each hydrogen injection pressure level. The engine was coupled to an eddy current dynamometer in an engine test bench configuration, which was used to apply and regulate the load during experimentation. All tests were conducted at a constant load of approximately 50% of the engine's rated load ($\approx$ 2.0 kW brake power). This load level was selected to ensure stable engine operation while allowing clear observation of the effects of hydrogen enrichment across the speed range.

Before recording data, the engine was allowed to reach steady-state operating conditions to minimize measurement uncertainty. Each test point was repeated to ensure repeatability and consistency of results, in accordance with standard experimental practices reported in hydrogen dual-fuel engine studies (Castro *et al* 2019, Bakar *et al* 2024).

Table 2. Measurement uncertainty.

Parameter	Instrument	Uncertainty
Engine speed	Tachometer	±10 rpm
Torque	Dynamometer	±0.1 Nm
Fuel consumption	Burette & stopwatch	±0.5%
CO, CO_2	Gas analyzer	±1%
NO_x	Gas analyzer	±2%
UHC	Gas analyzer	±2%

Fuel consumption for diesel was measured using a burette and stopwatch method, while hydrogen consumption was monitored through the regulated supply system. Brake power, torque, and brake mean effective pressure (BMEP) were obtained directly from the dynamometer readings.

3.4. Emission measurement and performance analysis

Exhaust emissions, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and unburned hydrocarbons (UHC), were measured using a calibrated exhaust gas analyzer. Emission sampling was conducted after ensuring stable exhaust temperature and steady engine operation. The selection of emission parameters followed common practices reported in hydrogen–diesel dual-fuel engine investigations (Lamas and Rodriguez 2019, Hosseini *et al* 2023).

BSFC, BTE, and BMEP were calculated using standard thermodynamic relations based on measured fuel consumption, brake power, and engine operating parameters. All calculated parameters were evaluated consistently across baseline diesel and hydrogen-enriched operating conditions to enable direct comparison.

3.5. Data reliability and safety considerations

To ensure data reliability, all sensors and measurement instruments were calibrated prior to testing. Hydrogen safety measures, including flame arrestors and leak checks, were implemented in accordance with established hydrogen engine testing protocols (Dhyani and Subramanian 2019, Khalid *et al* 2024). No abnormal combustion events, such as backfire or knocking, were observed during the experimental campaign.

3.6. Data reliability and safety

To ensure data reliability and repeatability, each experimental measurement was conducted three times at every operating condition, and the reported values represent the average of these repeated measurements. The variation between repeated readings was observed to be within an acceptable range, indicating good experimental consistency. All instruments were calibrated prior to testing to ensure measurement accuracy within the specified limits.

Besides, an uncertainty analysis was performed to evaluate the accuracy of the measured and calculated parameters. The uncertainties associated with key instruments were based on manufacturer specifications and standard experimental practices. The estimated uncertainties of the primary measured parameters are as follows: engine speed (±10 rpm), torque (±0.1 Nm), fuel consumption (±0.5%), and exhaust gas emissions (±1%–2% depending on the gas species). The measurement uncertainty parameter have been summarize in table 2.

The uncertainty in BSFC was calculated using standard error propagation as follows:

$$\frac{\Delta \text{BSFC}}{\text{BSFC}} = \sqrt{[(\dot{m}f/mf)^2 + (\Delta BP/BP)^2}$$

where:
$\dot{m}f$ = fuel mass flow rate
BP = brake power
Δ = corresponding uncertainty in measurement

The overall uncertainty in calculated parameters such as BSFC and BTE was estimated using standard error propagation methods. The maximum uncertainty was found to be within ±2.1% for BSFC and ±2.0% for BTE, which is within acceptable limits for ICE experimental studies.

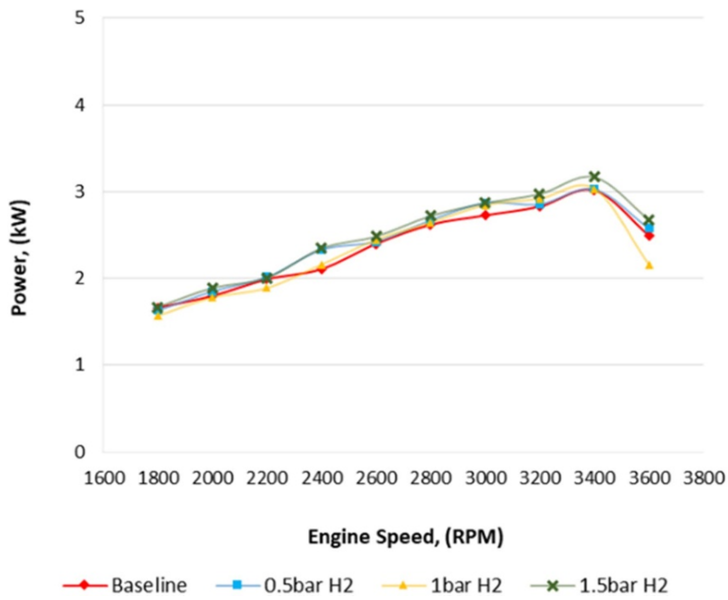

Figure 6. Variation of brake power with engine speed for diesel and hydrogen–diesel dual-fuel operation at different hydrogen injection pressures. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

4. Results and discussion

To enhance the quantitative interpretation of the experimental results, regression analysis was performed on key engine performance and emission parameters as a function of engine speed and hydrogen injection pressure.

A second-order polynomial regression model was selected due to the nonlinear behavior observed in ICE performance characteristics. The general form of the regression model is:

$$y = ax^2 + bx + c$$

where y represents the dependent variable (e.g. torque, brake power, BSFC, emissions), and x represents engine speed.

The regression analysis showed strong agreement with the experimental data across all parameters, with coefficients of determination (R^2) typically in the range of 0.94–0.99, indicating that the selected model adequately captures the nonlinear trends observed in the engine behavior.

Furthermore, the combined influence of engine speed and hydrogen injection pressure can be expressed using a two-variable regression model:

$$y = a + bx^1 + cx_2 + dx_1x_2$$

where x_1 represents engine speed and x_2 represents hydrogen injection pressure. This model highlights the coupled effects of operating parameters and confirms that engine performance and emissions are governed by their interaction rather than independent variation.

Error plots representing measurement uncertainty were evaluated for key parameters; however, due to the relatively small variation (within ±2%–3%), they are not prominently visible in the plots in the results plotting.

4.1. Engine performance characteristics

Figure 6 presents the variation of brake power with engine speed for diesel-only and hydrogen–diesel dual-fuel operation at different hydrogen injection pressures. Hydrogen enrichment resulted in a marginal increase in brake power across most engine speeds, with the highest values consistently observed at 1.5 bar hydrogen injection pressure. A maximum brake power of approximately 3.17 kW at 3400 rpm was recorded at this condition. Torque output followed a similar trend, as shown in figure 7, with slight improvements at higher hydrogen pressures.

The observed enhancement in brake power and torque is associated with the combined effect of increased hydrogen injection pressure and increased hydrogen energy contribution, which together promoted faster combustion and improved heat release characteristics. The outcomes are consistent with

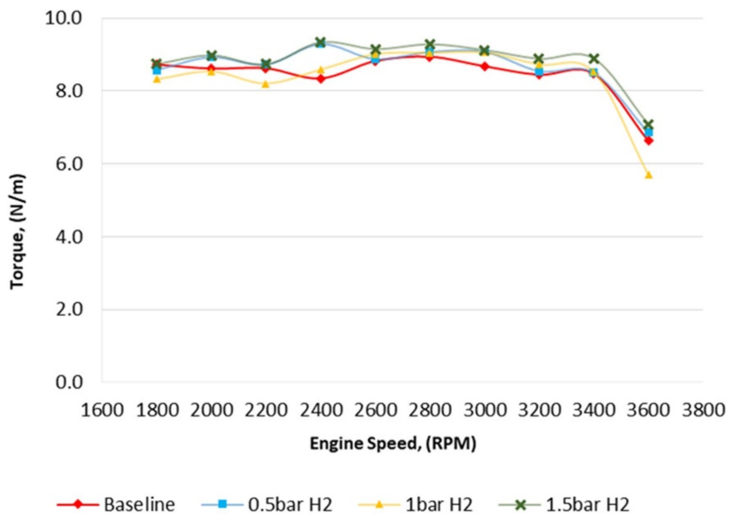

Figure 7. Torque variation with engine speed under diesel-only and hydrogen–diesel dual-fuel conditions. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

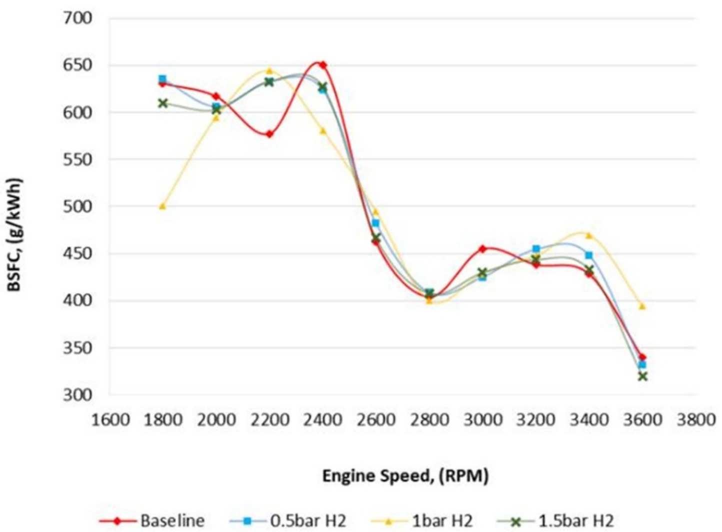

Figure 8. Brake specific fuel consumption variation with engine speed at different hydrogen injection pressures. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

the statements in their published research (Seelam *et al* 2022, Gültekin and Ciniviz, 2023a). Similar performance improvements under hydrogen–diesel dual-fuel operation have been reported by Castro *et al* (2019) and Bakar *et al* (2024). However, the relatively modest increase observed in the present study suggests that hydrogen injection pressure alone is insufficient to achieve substantial power gains without further optimization of injection timing and mixture formation, as also noted by Kumar *et al* (2022). For instance, regression analysis of torque and brake power at 1.5 bar hydrogen injection pressure showed a strong nonlinear relationship with engine speed, with R^2 values exceeding 0.97. The results indicate that engine performance increases with speed up to an optimal range (approximately 3000–3400 rpm), beyond which a decline is observed due to reduced volumetric efficiency and increased frictional losses.

The variation of BSFC with engine speed is shown in figure 8. Similarly, BSFC exhibited a decreasing trend with increasing engine speed, followed by stabilization at higher speeds. The regression model confirms that improved combustion efficiency at higher speeds contributes to reduced fuel consumption. Hydrogen enrichment led to a consistent reduction in BSFC compared to diesel-only operation, particularly at higher engine speeds. The minimum BSFC value of 320.12 g kWh^{-1} was achieved at 1.5 bar hydrogen injection pressure at 3600 rpm.

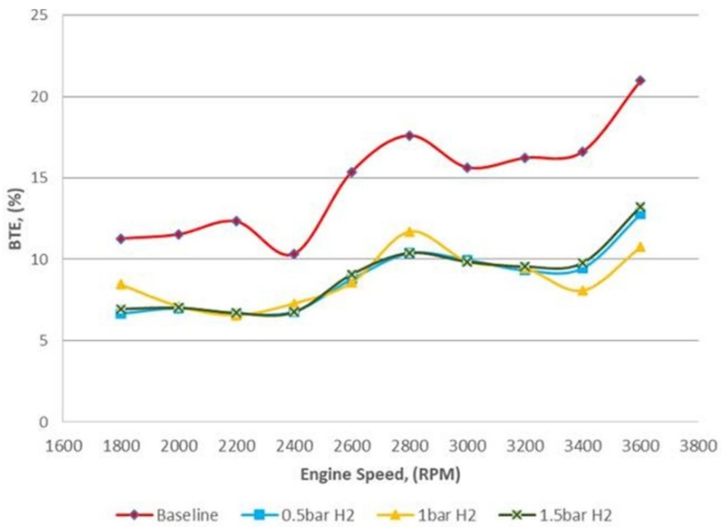

Figure 9. Brake thermal efficiency variation with engine speed for hydrogen–diesel dual-fuel operation. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

Correspondingly, BTE increased with hydrogen injection pressure, as illustrated in figure 9. The highest BTE of approximately 13.23% was obtained at 1.5 bar, indicating more efficient conversion of fuel energy into useful work.

These improvements are consistent with findings reported in previous studies, where hydrogen addition enhanced combustion efficiency due to reduced ignition delay and improved flame propagation (Seelam *et al* 2022, Gültekin and Ciniviz, 2023b). The superior performance at higher injection pressure suggests improved hydrogen–air mixing, which enhances combustion quality. Similar trends have been observed by Bayramoğlu and Yılmaz (2021), who highlighted the influence of hydrogen delivery parameters on engine efficiency. Although a peak BTE of 13.23% was achieved, the estimated improvement over baseline diesel operation is relatively modest (∼1–1.5 percentage points). Given the reported uncertainty (±2%), this improvement should be interpreted as moderate, highlighting the need for further optimization. As the maximum BTE obtained in the present study (∼13.23%) is lower than values commonly reported for larger or fully optimized diesel engines, this result should be interpreted within the context of the experimental operating conditions. The experiments were conducted using a small single-cylinder, naturally aspirated engine operating at approximately 50% load, where higher relative heat losses and lower combustion efficiency are typically observed. In addition, hydrogen was supplied through a PFI system, which may reduce volumetric efficiency due to intake air displacement by hydrogen within the intake manifold. This effect can limit oxygen availability and partially offset the combustion advantages associated with hydrogen enrichment. Furthermore, hydrogen injection timing and mixture preparation were not fully optimized in the present work, which may also contribute to the relatively modest BTE improvement observed.

4.2. Emission characteristics

Figure 10 illustrates the variation of carbon dioxide (CO_2) emissions with engine speed under diesel-only and hydrogen–diesel dual-fuel operation. CO_2 emissions decreased consistently with increasing hydrogen injection pressure across the entire speed range, with the lowest emissions recorded at 1.5 bar hydrogen pressure.

The reduction in CO_2 emissions is primarily attributed to hydrogen's carbon-free nature, which directly displaces a portion of carbon-based diesel fuel (Acar and Dincer 2020, Hosseini *et al* 2023). Similar reductions in CO_2 emissions under hydrogen–diesel operation have been widely reported in the literature (Castro *et al* 2019, Bakar *et al* 2024), confirming the decarbonization potential of hydrogen enrichment.

The variation of nitrogen oxides (NO_x) emissions with engine speed is presented in figure 11. NO_x emissions increased under conditions of higher hydrogen injection pressure, which also corresponded to higher hydrogen energy input. Therefore, the observed NO_x increase likely reflects the combined influence of enhanced hydrogen combustion intensity and elevated in-cylinder temperature rather than injection pressure alone, with peak values observed between 2600 and 3000 rpm.

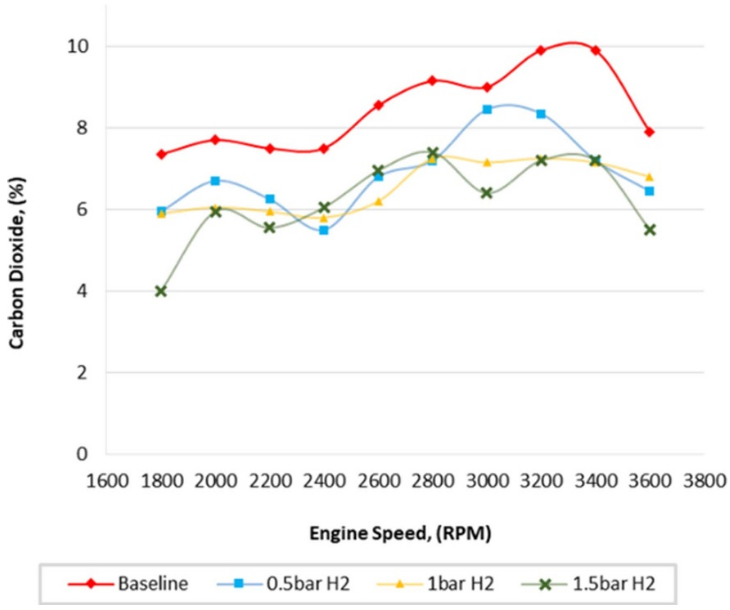

Figure 10. Carbon dioxide emission variation with engine speed under diesel and hydrogen–diesel dual-fuel operation. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

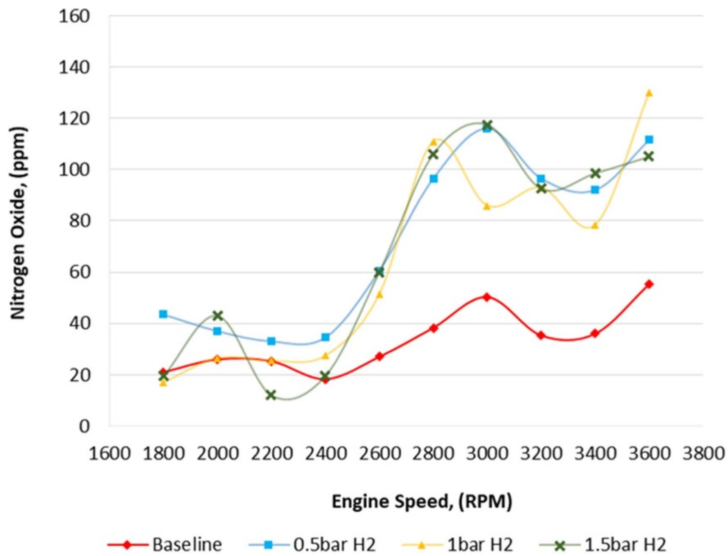

Figure 11. Nitrogen oxides emission variation with engine speed at different hydrogen injection pressures. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

This increase is consistent with numerous studies attributing elevated NO_x formation to higher in-cylinder temperatures associated with hydrogen's high flame speed and adiabatic flame temperature (Lamas and Rodriguez 2019, Kumar *et al* 2022, Bakar *et al* 2024). However, the non-monotonic trend observed at certain speeds suggests combustion instability and variations in local equivalence ratio, as also reported by Hosseini *et al* (2023). These findings reinforce that NO_x formation in hydrogen–diesel dual-fuel engines is highly sensitive to injection parameters rather than hydrogen addition alone.

Regression analysis of emission parameters revealed distinct nonlinear trends. CO_2 emissions decreased with increasing hydrogen injection pressure, while NO_x emissions showed a strong positive correlation with both engine speed and hydrogen enrichment. The regression models confirm that NO_x formation is highly sensitive to temperature variations, which increase with hydrogen addition. Meanwhile, CO and UHC emissions exhibited irregular trends, reflecting the complex interaction between mixture formation and combustion stability under PFI operation.

Carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions were higher under hydrogen–diesel operation compared to baseline diesel, particularly at lower engine speeds. This trend contrasts

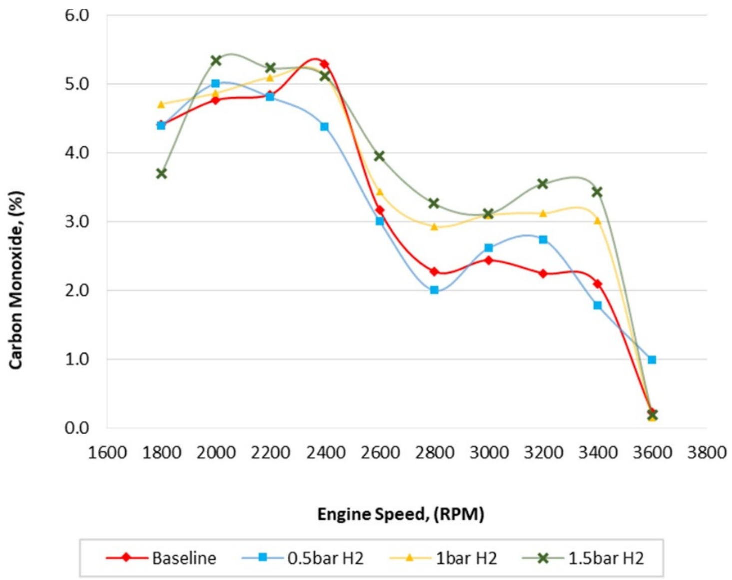

Figure 12. Carbon monoxide emission variation with engine speed at different hydrogen injection pressures. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

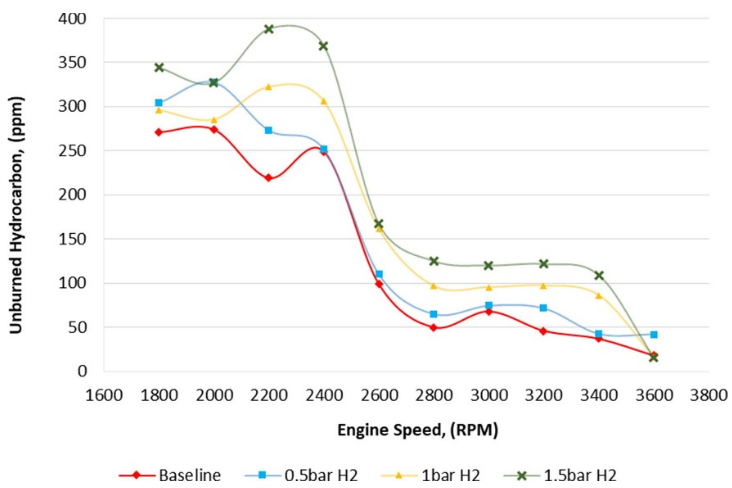

Figure 13. Unburned hydrocarbons emission variation with engine speed at different hydrogen injection pressures. Solid lines represent second-order polynomial regression fit ($R^2 > 0.95$).

with some studies reporting reduced CO and UHC emissions due to improved combustion efficiency (Castro *et al* 2019, Seelam *et al* 2022).

The increased CO and UHC emissions observed in the present study are likely attributed to non-optimized hydrogen injection timing and incomplete oxidation, especially at lower speeds where hydrogen–air mixing may be less effective as shown in figures 12 and 13. Similar increases in incomplete combustion products have been reported by Khatri and Khatri (2020) and Gültekin and Ciniviz (2023b), who emphasized the importance of coordinated pilot fuel and hydrogen injection strategies.

The results demonstrate that hydrogen injection pressure plays a critical role in determining the performance and emission behavior of hydrogen–diesel dual-fuel CI engines under PFI configuration. Higher injection pressure improved performance metrics such as BTE and BSFC, indicating enhanced combustion efficiency. However, increased NO_x emissions and incomplete combustion products highlight the trade-off between efficiency gains and emission penalties.

These findings help explain inconsistencies reported in previous studies, where variations in hydrogen delivery parameters led to contradictory emission trends (Pham *et al* 2022, Hosseini *et al* 2023). The present results confirm that injection pressure must be optimized in conjunction with injection timing and air–fuel management to fully exploit hydrogen's benefits while minimizing adverse emission effects.

The fluctuations observed in figures 6–13 across certain engine speed ranges can be attributed to several interacting physical and experimental factors associated with hydrogen–diesel dual-fuel combustion under PFI operation.

Firstly, variations in hydrogen–air mixture homogeneity play a significant role. At different engine speeds, the intake air velocity and turbulence intensity vary, affecting the mixing quality of hydrogen with air in the intake manifold. At lower speeds, insufficient turbulence may lead to non-uniform mixture distribution, while at higher speeds, reduced residence time may limit complete mixing, both contributing to cycle-to-cycle combustion variability.

Secondly, combustion instability is more pronounced in dual-fuel operation due to the wide flammability range and low ignition energy of hydrogen. Small variations in mixture composition can lead to fluctuations in ignition delay and combustion phasing, which directly influence BTE, BSFC, and emission characteristics.

In addition, nonlinear interactions between hydrogen injection pressure and volumetric efficiency may also contribute to the observed trends. Increasing hydrogen injection pressure can alter the intake charge dynamics, potentially displacing intake air and reducing volumetric efficiency at certain operating points. This effect is not strictly linear and can lead to irregular variations in engine performance parameters.

Furthermore, nitrogen oxides (NO_x) formation is highly sensitive to local in-cylinder temperature and oxygen availability. Even small variations in combustion temperature and equivalence ratio can result in noticeable fluctuations in NO_x emissions, particularly under hydrogen-enriched conditions where higher flame temperatures are expected.

Lastly, minor fluctuations may also be influenced by the dynamic response of measurement instruments during stepwise changes in engine speed. Despite careful calibration and repeated measurements, transient variations cannot be completely eliminated and are reflected in the experimental data.

Similar fluctuations have been reported in previous dual-fuel engine studies and are generally attributed to mixture inhomogeneity and combustion variability under varying operating conditions (Lamas and Rodriguez 2019, Khatri and Khatri 2020, Gültekin and Ciniviz, 2023b, Kumar *et al* 2022, Bakar *et al* 2024). Overall, the observed fluctuations are consistent with the complex and highly sensitive nature of hydrogen–diesel dual-fuel combustion, especially under varying engine speed and hydrogen injection pressure conditions.

5. Conclusion

This study experimentally investigated the influence of hydrogen injection pressure on the performance and emission characteristics of a hydrogen–diesel dual-fuel CI engine operating under PFI configuration. Hydrogen enrichment improved key performance indicators, including brake power, BTE, BMEP, and BSFC, with the most favorable results obtained at a hydrogen injection pressure of 1.5 bar. In terms of emissions, hydrogen addition resulted in a consistent reduction in carbon dioxide emissions, confirming the decarbonization potential of hydrogen-assisted diesel combustion. However, increases in nitrogen oxides, carbon monoxide, and unburned hydrocarbons were observed under certain operating conditions, particularly at higher injection pressures and lower engine speeds. These emission penalties highlight the sensitivity of hydrogen–diesel dual-fuel combustion to injection parameter optimization.

- Second-order polynomial models showed strong agreement with experimental data, with coefficients of determination ($R^2 > 0.95$).
- Optimal engine performance was observed in the mid-to-high speed range ($\approx$ 2800–3400)
- Hydrogen–diesel bi-fuel engines show improved combustion efficiency, resulting in enhanced power (0.5 bar, 2.52%) and (1.5 bar, 4.73%), torque (0.5 bar, 2.58%) and (1.5 bar, 4.72%),
- BMEP (0.5 bar, 2.58%) and (1.5 bar, 4.72%), and BSFC (1.5 bar, 0.65%)
- For instance, BTE was not improved by the hydrogen mixture at all but still 1.5 bar demonstrated the higher BTE (13.23%)
- Hydrogen–diesel bi-fuel was shown to reduce CO2 emissions (0.5 bar, 18.45%), (1 bar, 22.18%), and (1.5 bar, 26.53%) from the baseline.
- 1.5 bar of hydrogen proved to be the best choice to be used, as it significantly improved power (4.73%), torque (4.72%), BMEP (4.72%), BSFC (0.65%) and CO2 emission (26.53%)

The findings demonstrate that the combined variation of hydrogen injection pressure and hydrogen energy input significantly influences engine performance and emission behavior under the present PFI configuration. Since hydrogen mass flow rate was not independently controlled, the individual contribution of injection pressure could not be fully isolated. While higher injection pressures enhance performance, effective emission mitigation requires coordinated optimization of hydrogen injection timing, pilot fuel strategies, and air–fuel management. Although the observed BTE improvement was relatively modest, the results demonstrate the potential of hydrogen enrichment to improve combustion characteristics under partial-load dual-fuel operation. Further optimization of hydrogen flow control, injection timing, and air–fuel management is expected to improve overall thermal efficiency. In addition, regression analysis confirmed the nonlinear relationship between engine speed and key performance and emission parameters. The second-order polynomial models showed strong agreement with experimental data, with coefficients of determination (R^2) generally exceeding 0.95. This indicates that the observed trends are systematic and can be reliably predicted within the tested operating range. Overall, this study provides experimental evidence supporting hydrogen–diesel dual-fuel operation as a viable transitional technology toward cleaner ICEs, provided that injection parameters are carefully controlled.

The present study specifically addresses the limited experimental investigation of hydrogen injection pressure effects under low-pressure PFI configuration in hydrogen–diesel dual-fuel CI engines. Unlike many previous studies that primarily focused on hydrogen substitution ratio or injection timing, the current work evaluates the combined influence of pressure-regulated hydrogen supply across a wide engine speed range under constant-load operation. The findings therefore provide additional experimental insight into how hydrogen delivery characteristics influence combustion efficiency and emission formation in practical PFI-based dual-fuel systems. Future research should focus on optimizing hydrogen injection timing, implementing exhaust gas recirculation or water injection strategies for NO_x mitigation, and extending the investigation to transient operating conditions and multi-cylinder engines to enhance real-world applicability.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors certify that none of their known financial or personal affiliations or conflicts of interest impacted the research presented in this paper.

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References

Acar C and Dincer I 2020 The potential role of hydrogen as a sustainable transportation fuel to combat global warming *Int. J. Hydrog. Energy* **45** 3396–406

Akal D, Öztuna S and Büyükakın M K 2020 A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect *Int. J. Hydrog. Energy* **45** 35257–68

Babayev R, Andersson A, Dalmau A S, Im H G and Johansson B 2022 Computational comparison of the conventional diesel and hydrogen direct-injection compression-ignition combustion engines *Fuel* **307** 121909

Bakar R A, Kadirgama K, Ramasamy D, Yusaf T, Kamarulzaman M K, Aslfattahi N and Alwayzy S H 2024 Experimental analysis on the performance, combustion/emission characteristics of a DI diesel engine using hydrogen in dual fuel mode *Int. J. Hydrog. Energy* **52** 843–60

Bayramoğlu K and Yılmaz S 2021 Emission and performance estimation in hydrogen injection strategies on diesel engines *Int. J. Hydrog. Energy* **46** 29732–44

Boretti A 2019 Advantages and disadvantages of diesel single and dual-fuel engines *Front. Mech. Eng.* **5** 64

Carlucci A P, Ficarella A, Strafella L and Trullo G 2020 Comprehensive characterization of the behavior of a diesel oxidation catalyst used on a dual-fuel engine *J. Energy Eng.* **146** 04020055

Castro N, Toledo M and Amador G 2019 An experimental investigation of the performance and emissions of a hydrogen-diesel dual fuel compression ignition internal combustion engine *Appl. Therm. Eng.* **156** 660–7

Demir U, Kozan A and Özer S 2022 Experimental investigation of the effect of urea addition to fuel on engine performance and emissions in diesel engines *Fuel* **311** 122578

Dhyani V and Subramanian K A 2019 Control of backfire and NOx emission reduction in a hydrogen fueled multi-cylinder spark ignition engine using cooled EGR and water injection strategies *Int. J. Hydrog. Energy* **44** 6287–98

El Shenawy E A, Elkelawy M, Bastawissi H A E, Panchal H and Shams M M 2019 Comparative study of the combustion, performance, and emission characteristics of a direct injection diesel engine with a partially premixed lean charge compression ignition diesel engines *Fuel* **249** 277–85

Furuhama S and Fukuma T 1986 High output power hydrogen engine with high pressure fuel injection, hot surface ignition and turbocharging *Int. J. Hydrogen Energy* **11** 399–407

Gültekin N and Ciniviz M 2023a Examination of the effect of combustion chamber geometry and mixing ratio on engine performance and emissions in a hydrogen-diesel dual-fuel compression-ignition engine *Int. J. Hydrogen Energy* **48** 2801–20

Gültekin N and Ciniviz M 2023b Experimental investigation of the effect of hydrogen ratio on engine performance and emissions in a compression ignition single cylinder engine with electronically controlled hydrogen-diesel dual fuel system *Int. J. Hydrog. Energy* **48** 25984–99

Hosseini S H, Tsolakis A, Alagumalai A, Mahian O, Lam S S, Pan J and Aghbashlo M 2023 Use of hydrogen in dual-fuel diesel engines *Prog. Energy Combust. Sci.* **98** 101100

Ikegami M, Miwa K and Shioji M 1982 A study of hydrogen fuelled compression ignition engines *Int. J. Hydrog. Energy* **7** 341–53

Jayakumar A, Madheswaran D K, Kannan A M, Sureshvaran U and Sathish J 2022 Can hydrogen be the sustainable fuel for mobility in India in the global context? *Int. J. Hydrog. Energy* **47** 33571–96

Khalid A H, Said M F M, Veza I, Abas M A, Roslan M F, Abubakar S and Jalal M R 2024 Hydrogen port fuel injection: review of fuel injection control strategies to mitigate backfire in internal combustion engine fuelled with hydrogen *Int. J. Hydrog. Energy* **66** 571–81

Khatri N and Khatri K K 2020 Hydrogen enrichment on diesel engine with biogas in dual fuel mode *Int. J. Hydrog. Energy* **45** 7128–40

Kumar M, Bhowmik S and Paul A 2022 Effect of pilot fuel injection pressure and injection timing on combustion, performance and emission of hydrogen-biodiesel dual fuel engine *Int. J. Hydrog. Energy* **47** 29554–67

Lamas M I and Rodriguez C G 2019 NOx reduction in diesel-hydrogen engines using different strategies of ammonia injection *Energies* **12** 1255

Li Y, Chen H, Zhang C and Chen H 2021 Effects of diesel pre-injection on the combustion and emission characteristics of a common-rail diesel engine fueled with diesel-methanol dual-fuel *Fuel* **290** 119824

Liu X, Srna A, Yip H L, Kook S, Chan Q N and Hawkes E R 2021 Performance and emissions of hydrogen-diesel dual direct injection (H2DDI) in a single-cylinder compression-ignition engine *Int. J. Hydrog. Energy* **46** 1302–14

Menaa A, Lounici M S, Amrouche F, Loubar K and Kessal M 2019 CFD analysis of hydrogen injection pressure and valve profile law effects on backfire and pre-ignition phenomena in hydrogen-diesel dual fuel engine *Int. J. Hydrog. Energy* **44** 9408–22

Mohammed S E, Aziz A R A, Baharom M B, Jaffry A and Ismael M A 2021 Effect of aspect ratio on the performance characteristics of free piston linear generator engine fueled by hydrogen *Int. J. Hydrog. Energy* **46** 10506–17

Moriarty P and Honnery D 2019 Prospects for hydrogen as a transport fuel *Int. J. Hydrog. Energy* **44** 16029–37

Park C, Kim Y, Oh S, Oh J, Choi Y, Baek H and Lee K 2022 Effect of fuel injection timing and injection pressure on performance in a hydrogen direct injection engine *Int. J. Hydrogen Energy* **47** 21552–64

Pham Q, Park S, Agarwal A K and Park S 2022 Review of dual-fuel combustion in the compression-ignition engine: spray, combustion, and emission *Energy* **250** 123778

Pyrc M, Gruca M, Jamrozik A, Tutak W and Juknelevičius R 2021 An experimental investigation of the performance, emission and combustion stability of compression ignition engine powered by diesel and ammonia solution (NH4OH) *Int. J. Engine Res.* **22** 2639–53

Seelam N, Gugulothu S K, Reddy R V, Bhasker B and Panda J K 2022 Exploration of engine characteristics in a CRDI diesel engine enriched with hydrogen in dual fuel mode using toroidal combustion chamber *Int. J. Hydrog. Energy* **47** 13157–67

Tripathi G, Sharma P, Dhar A and Sadiki A 2019 Computational investigation of diesel injection strategies in hydrogen-diesel dual fuel engine *Sustain. Energy Technol. Assess.* **36** 100543

US EPA 2024 June 20 Particulate matter (PM) basics|US EPA World Wide Web (available at: www.epa.gov/pm-pollution/particulate-matter-pm-basics)

Yang B, Ning L, Liu B, Huang G, Cui Y and Zeng K 2021 Comparison study the particulate matter characteristics in a diesel/natural gas dual-fuel engine under different natural gas-air mixing operation conditions *Fuel* **288** 119721

Yang Z, Wu J, Yun H, Zhang H and Xu J 2022 Diagnosis and control of abnormal combustion of hydrogen internal combustion engine based on the hydrogen injection parameters *Int. J. Hydrog. Energy* **47** 15887–95

Yip H L, Srna A, Yuen A C Y, Kook S, Taylor R A, Yeoh G H and Chan Q N 2019 A review of hydrogen direct injection for internal combustion engines: towards carbon-free combustion *Appl. Sci.* **9** 4842