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The Impact of Water Injection and Hydrogen Fuel on Performance and Emissions in a Hydrogen/Diesel Dual-Fuel Engine

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Abstract: As the need for alternative energy sources and reduced emissions grows, proven technologies are often sidelined in favour of emerging solutions that lack the infrastructure for mass adoption. This study explores a transitional approach by modifying existing compression ignition engines to run on a hydrogen/diesel mixture for performance improvement, utilising water injection to mitigate the drawbacks associated with hydrogen combustion. This approach can yield favourable results with current technology. In this modelling study, ten hydrogen energy ratios (0–90%) and nine water injection rates (0–700 mg/cycle) were tested in a turbocharged Cummins ISBe 220 31 six-cylinder diesel engine. An engine experiment was conducted to validate the model. Key performance indicators such as power, mechanical efficiency, thermal efficiency, indicated mean effective pressure (IMEP), and brake-specific fuel consumption (BSFC) were measured. Both water injection and hydrogen injection led to slight improvements in all performance metrics, except BSFC, due to hydrogen's lower energy density. In terms of emissions, CO and CO_2 levels significantly decreased as hydrogen content increased, with reductions of 94% and 96%, respectively, at 90% hydrogen compared to the baseline diesel. Water injection at peak rates further reduced CO emissions by approximately 40%, though it had minimal effect on CO_2. As expected, NOx (which is a typical challenge with hydrogen combustion and also with diesel engines in general) increased with hydrogen fuelling, resulting in an approximately 70% increase in total NOx emissions over the range of 0–90% hydrogen energy. Similar increases were observed in NO and NO_2, e.g., 90% and 57% increases with 90% hydrogen, respectively. However, water injection reduced NO and NO_2 levels by up to 16% and 83%, respectively, resulting in a net decrease in NO_X emissions in many combined cases, not only with hydrogen injection but also when compared to baseline diesel.

Keywords: hydrogen combustion; dual-fuel hydrogen/diesel engine; NOx; performance; emissions

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1. Introduction

The rising stringency of emissions standards, coupled with the increasing costs and finite availability of fossil fuels, necessitate the need to further improve the emissions and fuel efficiency of internal combustion engines [1,2]. A potential solution to both challenges is the use of hydrogen as a fuel additive for existing engines [3]. Hydrogen is abundant, can be produced with renewable resources, and has sufficient energy to substitute carbon-based fuel in the combustion process, thereby reducing carbon emissions [4,5]. Various methods have successfully modified diesel engines to run on up to 90% hydrogen, improving thermal efficiency [6]. However, the higher combustion temperature associated with hydrogen use increases the risk of knocking due to the lean mixture and elevates the quantity of thermal NO_X [4,7], which is a big challenge for diesel engines in terms of emissions regulations [2,8]. Such drawbacks pose significant barriers to the widespread adoption of hydrogen/diesel technology [9].

Hydrogen can be employed in existing diesel engines as a dual-fuel mode without significant modification. Multiple methods of introducing hydrogen to the combustion process in compression ignition (CI) engines have been researched, including carburetion, port injection, and direct injection [4], though direction injection offers significant advantages over the alternatives. More precise fuel delivery, improved combustion, increased power, increased economy (up to 15%), and reduced emissions (up to 25% on cold starts), as well as the ability to add fuel to the combustion chamber after the intake valve has been closed (thereby reducing pre-ignition and removing backfire concerns), are some benefits of hydrogen direct injection (H_2DI) [4,6]. Carburetion and port injection methods, on the other hand, suffer from reduced volumetric efficiency, as H_2 displaces oxygen in the intake [5,7].

Neat hydrogen cannot be combusted well in a CI engine as it does not have a low enough compression ratio or auto-ignition temperature [5,7]. In dual-fuel mode, a CI engine can overcome this by igniting the compressed mixture of air and hydrogen via injection of a small amount of diesel into the cylinder as a "pilot fuel" [4]. Neat hydrogen can be combusted in spark-ignition (SI) engines, but it suffers from ignition delay in this application as a result of its high self-ignition temperature [4]. It is, however, a suitable option in gas/diesel dual-fuel engines when compared to alternatives such as compressed natural gas or liquid petroleum gas due to its fast flame speed and broad flammability range [4]. Additionally, hydrogen/diesel dual-fuel (H_2DDF) engines could employ the benefit of reverting to neat diesel combustion if H_2 is depleted and/or unavailable [5]. By substituting diesel fuel with hydrogen in H_2DDF engines, overall carbon emissions (including unburnt hydrocarbons), soot, and smoke are reduced [4,7]. A previous study found that for all hydrogen energy fractions, CO emissions were low enough to not be measurable and that almost five times fewer carbon dioxide emissions are produced at 90% hydrogen energy [6].

It has been recommended that future studies explore direct injection of hydrogen due to its superior performance and emissions over port injection or carburetion methods [7]. However, significant attention must be devoted to mitigating NOx emissions [4]. NO_X emissions are generated through the breakdown of nitrogen in the atmospheric air used as an oxidiser for the combustion process (thermal NO_X), as well as the breakdown of nitrogen content in fuels (fuel NO_X). During combustion, the stable nitrogen (N_2) in the air dissociates into reactive nitrogen (N), which becomes highly active at temperatures between 2500 and 3000 K [10]. By substituting the majority of the diesel fuel with hydrogen, the fuel NO_X concern is mitigated [4]; however, the elevated combustion temperatures associated with hydrogen significantly increase the formation of thermal NO_X [9,10]. NO_X emissions have been shown to already exceed safe limits in urban areas [10], posing a serious risk to public health and the environment. These emissions contribute to respiratory diseases such as lung irritation, reduced lung immunity, oedema, bronchitis, and pneumonia [11], and they also exacerbate global warming [10].

Liu et al. [6] found that for hydrogen energy fractions between 30 and 90%, NO_X levels are in the range of 10–23 g/kWh compared to the diesel baseline of 6.4 g/kWh. Another study found that NO_X increased by 18% with the addition of hydrogen in dual-fuel mode [7]. However, it has also been theorised that water produced during the combustion of H_2 may lower in-cylinder temperature and decrease NO_X emissions slightly and that the higher diffusivity of hydrogen may decrease the number of fuel-rich areas in the cylinder, meaning fewer 'hot spots' and more uniform temperature rise, also slightly lowering NO_X production [4]. Moreover, Gültekin and Ciniviz [7] found that when the engine load was low, the addition of hydrogen actually reduced NO_X emissions. At high loads, however, the expected significant increase in NO_X emissions was present.

Water injection (WI) can be considered as a method for reducing NO_X emissions from hydrogen combustion. WI is a promising solution to mitigate the high combustion temperature, which, under optimal conditions, has been shown to reduce NO_X emissions by up to 70% [12]. WI in internal combustion engines, including CI engines, is tried and tested. Experimentation with the technology dates back over a century, and it was used extensively during World War II [1,13]. In recent decades, it has resulted in some commercial success [13]. Multiple methods of introducing WI have been studied, including humidification of intake air, single-point or intake manifold water injection (IMWI), multi-point or port WI, direct water injection (DWI), fuel–water emulsion, and hybrids of these methods [13].

The goal of WI is to achieve efficient cooling of hot areas inside the cylinder. This is achieved due to its higher specific heat capacity than air alone. When water vaporises, as per Equation (1), the energy required removes significant heat from the cylinder [13], leading to further effects discussed in this paper.

$$\dot{m_w} \cdot \Delta h_{ev} = \dot{m_a} \cdot c_P \cdot \Delta T_a \tag{1}$$

Studies have shown that the temperature of liquid water injected does not substantially affect its impact on combustion performance or emissions [9,12]. In this way, WI offers a promising solution to lowering the in-cylinder temperature, which in turn decreases NO_X emissions [1]. Additionally, by cooling intake and in-cylinder temperatures, water works to decrease knock and thermal stresses [1]. However, this process may also increase the formation of particulate matter [13], which could be mitigated by after-treatment systems such as diesel particulate filters (DPF) [14].

One of the most common solutions for NO_X reduction currently employed by industry is that of exhaust gas recirculation (EGR). EGR has been shown to produce comparable reductions in NO_X when compared to WI; however, it has detrimental effects on performance [12,15]. Additionally, EGR deteriorates combustion quality, leading to increased hydrocarbon, carbon monoxide [16], and soot emissions [17]. WI may be considered a more suitable method of reducing NO_X emissions without relying on EGR or other after-treatment strategies as the only options [1,13].

The methods by which WI can reduce NO_X are through dilution, temperature, and chemistry. The dilution method is characterised by nitrogen from the intake being displaced by water [2]. This can be the most effective means by which WI reduces NO_X [1,2]. However, it does lead to incomplete combustion and a reduction in the combustion rate, worsening fuel consumption and CO emissions [2]. The temperature method consists of the high latent heat of vaporisation and the specific heat capacity of water, allowing it to cool the combustion chamber, thereby reducing NO_X [2,12]. This also delays the start of combustion and increases the quality of the air/fuel mixture, which speeds up the duration of combustion and can potentially reduce fuel consumption [2], though this is not generally observed in practice for CI engines, as discussed earlier in this paper. Studies have shown that in some applications, this method can have a 3–4 times greater impact on NO_X reduction than the dilution method [8]. Finally, the chemistry method, which rarely has any measurable effect, describes the process in which hydroxyl radicals are formed in the cylinder, combining with would-be NO_X emissions to form HNO_3 instead [1,2,8].

Water injection has also been shown to reduce and increase particulate emissions [12], depending on its application. For example, Fan et al. [18] found that both NO_X and particulate matter (PM) could be reduced under different test cases. Despite the fact that PM and NO_X emissions are usually inversely related, and so reducing one typically increases the other, water injection was shown as a technique for reducing both nitrogen oxides and particulates simultaneously; it is capable of reducing NO_X emissions through the methods discussed already and also reduces particulates by displacing fuel in otherwise fuel-rich areas of the combustion chamber, promoting fuel diffusivity [8,19]. However, under some conditions, WI can increase PM emissions while reducing NO_X. Bedford et al. [20] found that while some methods of water injection were successful at reducing NO_X and PM, stratified fuel/water injection was found to increase PM due to late injection timing. It was recommended that as the NO_X benefits of water injection are well established regardless of the method of injection, future works should aim to optimise WI for soot emissions. Additionally, as stated, existing industry solutions such as DPF could mitigate these effects [14].

In terms of alternative fuels, both modelling [12] and experimental studies [21] have shown that DWI can reduce NO_X emissions in diesel or biodiesel engines by approximately

56%. However, not much research has been done in the field of H_2DDF engines with WI, although it is a viable potential solution to the NO_X problem [1]. A limited number of recent studies have attempted to employ WI to prevent intake self-ignition, combustion knocking, and NO_X emissions in port-injected H_2DDF engines [5]. Slightly more research has been done on neat hydrogen combustion in CI engines with WI [9].

It has been shown that decreases in NO_X of more than 85% are possible with both port injection and direct injection of water in neat hydrogen engines [1]. Another two experimental studies were able to achieve upwards of a 50% reduction in NO_X at both low and high engine loads with IMWI in neat hydrogen engines, though one was not a CI engine [1,5].

An increase in the amount of water injected allows for an increase in the hydrogen energy fraction as self-ignition and knocking are controlled, therefore allowing a greater hydrogen energy fraction and less carbon-based fuel required to meet the same performance metrics. In fact, WI has been shown to improve the stable hydrogen share of an experimental dual-fuel CI engine from 18% to 66%, and further to 79% with a reduced compression ratio [1].

This study aims to address the recommendations of previous studies by expanding the literature in this area through investigation of the effects of IMWI (due to its economic advantages over DWI or other methods) and H_2DI (due to its performance and emissions advantages over carburetion and port injection, as well as the reduced amount of literature available on this method) on power and emissions in H_2DDF engines across a broad range of WI rates and H_2 energy fractions. This study also evaluates NOx emissions in more detail by investigating NO and NO_2 emissions, which are under-represented in the literature. Furthermore, given that the higher calorific value of hydrogen compared to diesel leads to higher power output and also impacts other parameters, this is the basis for data explanation and interpretation in some of the relevant studies in the literature [5] because of their design of experiments. However, this study designed the experiments in a way that fuel mixtures have the same calorific value, which facilitates better analysis and understanding of other fuel properties.

2. Methodology

2.1. Experimental Set-Up

The engine used in this modelling study is a Cummins ISBe 220 six-cylinder turbocharged diesel engine; the specification is presented in Table 1. To validate the model, an experiment was conducted at the laboratory by running the engine attached to a hydraulic dynamometer and recording the required data (e.g., power, torque, in-cylinder data, etc.), as detailed in Figure 1.

Table 1. Cummins ISBe 220 31 engine specifications.

Parameter	Unit	Value
Bore	mm	102
Stroke	mm	120
Connecting rod length	mm	220
Displacement	L	5.9
Maximum power	kW @ rpm	162 @ 2000
Maximum torque	Nm @ rpm	820 @ 1500
Compression ratio	-	17.3:1
Firing order	-	1-5-3-6-2-4

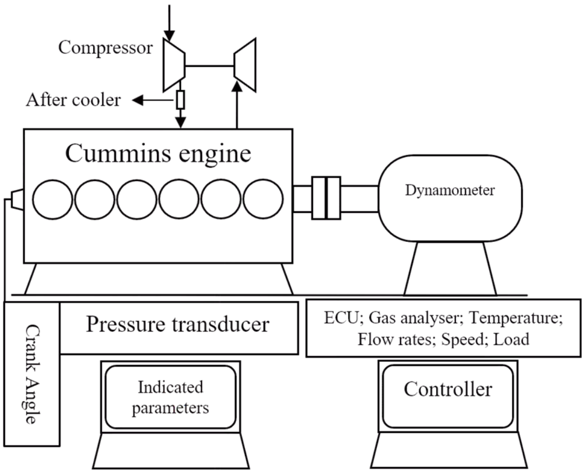

Figure 1. Schematic detailing experimental set-up.

2.2. Engine Model

AVL Boost has been employed to model the Cummins ISBe 220 engine. The engine model is shown in Figure 2. As can be seen, the model consists of two system boundaries representing the intake and exhaust: a turbocharger, an intercooler, an injector for water, an intake plenum, and six cylinders.

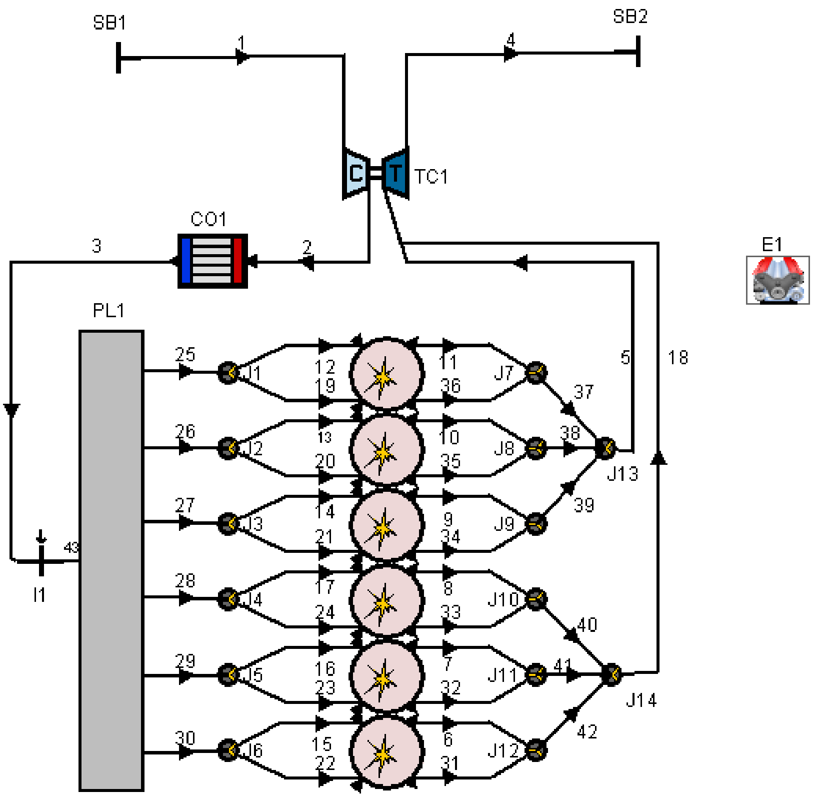

Figure 2. AVL Boost model of the modified Cummins ISBe 220 engine.

2.3. Emission and Combustion Models

The emissions results are solved with direct calculation using the reactions listed in Table 2.

Table 2. AVL CO and NOx formation models [22].

Stoichiometry	$Rate\left(\text{mole}/\text{cm}^3\text{s}\right)$	$k_0\left(\text{cm}^3, \text{mol}, \text{s}\right)$	$a(-)$	$T_A(K)$
		Carbon		
$CO + OH = CO_2 + H$	$\mathrm{r}_1 = 6.76 \times 10^{10} \cdot \mathrm{e}^{\left(\frac{\mathrm{T}}{1102.0}\right)} \cdot \mathrm{c}_{\mathrm{CO}} \cdot \mathrm{c}_{\mathrm{OH}}$ (2)	-	-	-
$CO + O_2 = CO_2 + O$	$r_2 = 2.51 \times 10^{12} \cdot e^{\left(\frac{-24055.0}{T}\right)} \cdot c_{CO} \cdot c_{O2}$ (3)	-	-	-
	Nitrous oxides, based on the Zeldovich mechanism, and where:			
	$\mathrm{k}_\mathrm{i} = \mathrm{k}_{0,\mathrm{i}} \cdot \mathrm{T}^\mathrm{a} \cdot \mathrm{e}^{\left(\frac{-\mathrm{TA}_\mathrm{t}}{\mathrm{T}}\right)}$ (4)			
$N_2 + O = NO + N$	$r_1 = k_1 \cdot c_{N2} \cdot c_O$ (5)	4.93×10^{13}	0.0472	38,048.01
$O_2 + N = NO + O$	$r_2 = k_2 \cdot c_{O2} \cdot c_N$ (6)	1.48×10^8	1.5	2859.01
$N + OH = NO + H$	$r_3 = k_3 \cdot c_N \cdot c_{OH}$ (7)	4.22×10^{13}	0.0	0.0
$N_2O + O = NO + NO$	$r_4 = k_4 \cdot c_{N2O} \cdot c_O$ (8)	4.58×10^{13}	0.0	12,130.6
$O_2 + N_2 = N_2O + O$	$r_5 = k_5 \cdot c_{O2} \cdot c_{N2}$ (9)	2.25×10^{10}	0.825	50,569.7
$OH + N_2 = N_2O + H$	$r_6 = k_6 \cdot c_{OH} \cdot c_{N2}$ (10)	9.14×10^7	1.148	36,190.66

The rate of CO conversion in $\text{mol}/\text{cm}^3\text{s}$ is given as:

$$r_{CO} = C_{Const} \cdot (r_1 + r_2) \cdot (1 - \alpha) \tag{11}$$

where

$$\alpha = \frac{c_{CO,act}}{c_{CO,equ}} \tag{12}$$

The rate of NO conversion in $\text{mol}/\text{cm}^3\text{s}$ is given as:

$$r_{NO} = C_{PostProcMult} \cdot C_{KineticMult} \cdot 2.0 \cdot \left(1 - \alpha^2\right) \cdot \left(\frac{r_1}{1 + \alpha \cdot AK_2} + \frac{r_4}{1 + AK_4}\right) \tag{13}$$

where

$$\alpha = \frac{C_{NO,act}}{C_{NO}, equ}, AK_2 = r\frac{1}{r_2 + r_3} \tag{14}$$

and

$$AK_4 = r\frac{4}{r_5 + r_6} \tag{15}$$

The vibe two-zone combustion model was employed to calculate the heat release of the engine. In this model, the combustion chamber is considered as two zones: the burnt zone and the unburnt zone, which each contain different substances at different temperatures and volumes [22,23]. In addition, the Woschni/Anisits model is used to determine internal heat transfer in the engine.

2.4. Model Validation Against Experimental Data

Experimental in-cylinder pressure, as well as the engine power and torque, were used to validate the model, as shown in Figures 3 and 4. As can be seen, the in-cylinder pressure recorded in Cylinder 6 at 2000 rpm and under full load correlated well with its experimental counterpart, especially in the range of compression and ignition, where less than ±5% error is observed. Additionally, the simulated power and torque curves show similar trends to the experimental data, with less than ±0.60% error observed.

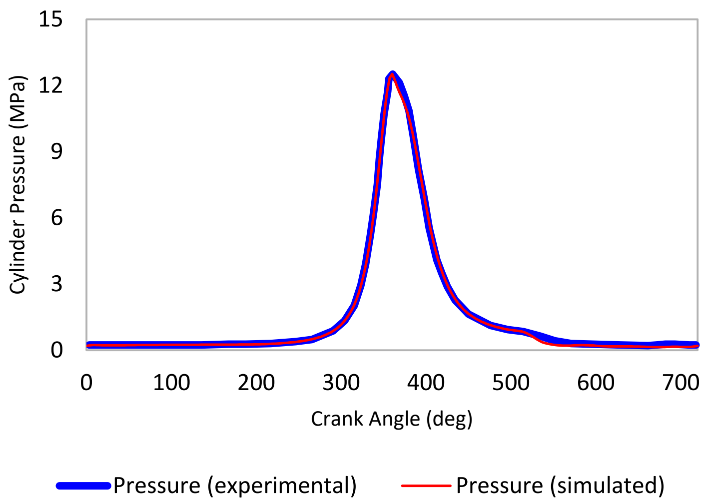

Figure 3. Comparison of experimental and simulated in-cylinder pressure at 2000 rpm at full load.

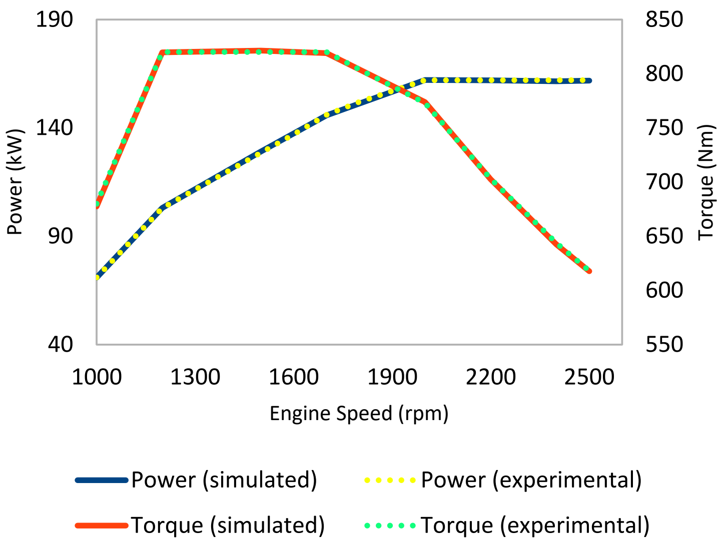

Figure 4. Comparison of experimental and simulated power and torque curves.

Regarding the test repeatability and uncertainty analysis, this study repeated the experiment three times and used the coefficient of variation (CV) statistical parameter to evaluate two critical operating parameters: engine load and speed. The low variation between repeated tests (less than 2% CV for the engine load and 1% CV for engine speed) indicates strong repeatability. Furthermore, this study utilised a high-quality CO_2 gas analyser (non-dispersive infrared CAI-600) to measure CO_2 across tests, assessing both repeatability and lab uncertainty. This approach is widely trusted in the automotive industry for emissions lab uncertainty measurements. The results showed that the CV between the repeated tests was less than 1%. More analysis of the in-cylinder data showed that the CV for maximum in-cylinder pressure and maximum rate of pressure rise were less than 1%.

2.5. Hydrogen and Water Injection

The model was then modified to simulate H_2DI (hydrogen direct injection) and IMWI (intake manifold water injection) by including hydrogen in the fuel mixture and adding the water injector prior to the intake plenum. A series of baseline results were collected at 2000 rpm, full load, with zero water injection and varying hydrogen-to-diesel ratios to study the pure impact of hydrogen on performance and emissions before the same tests were repeated with increasingly higher water-to-fuel ratios. Ten hydrogen-to-diesel energy ratios were considered between 0 and 90%, as well as nine water mass quantities between 0 and 700 mg/cycle, where the injected diesel quantity is that of the baseline engine. Taking the energy density of hydrogen at 120 MJ/kg and diesel at 44.8 MJ/kg (Table 3), the total fuel quantities shown in Table 4 were determined for each hydrogen fraction in order to maintain constant intake calorific energy.

Table 3. Fuel properties of diesel and hydrogen [24–29].

Property	Diesel	Hydrogen
C (wt%)	85.1	0
H (wt%)	14.8	100
Heating value (MJ/kg)	44.8	120
Auto ignition temp. in air (°C)	260	585
Flame velocity at 25 °C and 1 atm (m/s)	0.3	2.37
Density at 25 °C and 1 atm (g/cc)	0.83	0.81×10^{-4}
Diffusion coefficient D12 at 25 °C and 1 atm (cm^2/s)	0.05–0.1	1.153

Table 4. Required fuel quantities to maintain constant calorific energy.

Hydrogen Percentage (by Mass)	Fuel Required (mg/cycle)
0	93.50
10	80.02
20	69.94
30	62.12
40	55.86
50	50.76
60	46.51
70	42.91
80	39.83
90	37.17

It is noted that while the selected hydrogen energy ratios and water injection rates may appear extreme, they are comparable to other values in the literature, such as the 90% energy fraction employed by Liu et al. [6] and the 48 kg/h (800 mg/cycle) employed by Serrano et al. [5] on a considerably smaller, four-cylinder engine. Additionally, most studies on H_2DDI engines focus on smaller hydrogen energy fractions [5,7], so as a point of difference, this study aims to extend the research to higher hydrogen concentrations.

For the purposes of reducing emissions further, these higher concentrations may be more applicable to steady-state stationary applications.

3. Results and Discussion

This section first evaluates the impact of water injection and hydrogen fuel on performance parameters such as power, indicated mean effective pressure (IMEP), mechanical efficiency, thermal efficiency, and brake-specific fuel consumption (BSFC) and then on emission parameters (CO, CO_2, NO_X, NO, and NO_2). The method of analysis is to first look at the effect of hydrogen variation (with no water injection) on each parameter and then evaluate the impact of water injection.

3.1. Performance

3.1.1. Power and IMEP

Figure 5a shows the results of increasing the hydrogen and water concentrations in the compression ignition engine as it relates to power output. As can be seen, increasing the share of hydrogen in the fuel mixture leads to higher power output, equating to an approximately 8.8% power increase for the 90% hydrogen case when compared to the engine running on neat diesel. A higher power output would typically be expected when hydrogen is introduced into the fuel mixture as a substitute for diesel due to the higher calorific value of hydrogen compared to diesel. However, as the calorific value of the fuel mixture is held constant across all cases in this study, the increase in performance with an increased hydrogen share can be attributed to the faster flame speed, high diffusivity, and high energy content of hydrogen, which have been shown to improve the performance of diesel engines when H_2DDF mode is employed [4,5]. The high diffusivity of hydrogen aids the combustion [4], enabling higher peak cylinder pressures and increased power output, particularly under high load conditions. This is due to hydrogen's rapid combustion in a quasi-constant volume environment, which results in near-instantaneous energy release compared to conventional diesel combustion [7,9]. It is also shown that hydrogen injection resulted in a 7.9% increase in IMEP for the 90% energy ratio compared to neat diesel combustion for the same reasons (Figure 5b). This agrees with the literature, which states that IMEP values similar to or above those of pure diesel are achievable for all hydrogen energy ratios [6].

The impact of water injection on power output was minimal, with only a 0.5% increase observed in the 700 mg/cycle case compared to the baseline engine without water injection. This finding aligns with theoretical predictions, which suggest that at high temperatures, water can dissociate into hydrogen and oxygen. These dissociated species may participate in the combustion process, potentially enhancing combustion efficiency. However, it is also possible that they form radicals, which can affect combustion in different ways depending on the specific conditions within the cylinder [8]. Additionally, water, when injected before the intake valve closes, can cool the intake air charge, slightly increasing air density and, thus, marginally boosting power output [1]. However, this effect is delicate. Excessive water injection can displace oxygen in the intake air, reducing the oxygen available for combustion [2]. In engines equipped with highly efficient intercoolers, the intake air may already be near saturation at 100% relative humidity. In such cases, a larger proportion of the injected water vaporises inside the cylinder during compression, leading to less cooling of the intake air and, consequently, a diminished effect on power output [1]. It is also shown in Figure 5b that water injection results in a negligible 0.39–0.46% increase in IMEP (across the 0–90% hydrogen energy ratios) for the 700 mg/cycle case compared to the engine with zero water injection for largely the same reasons. This, too, agrees with the literature, which states that WI in CI engines has little impact on IMEP [13].

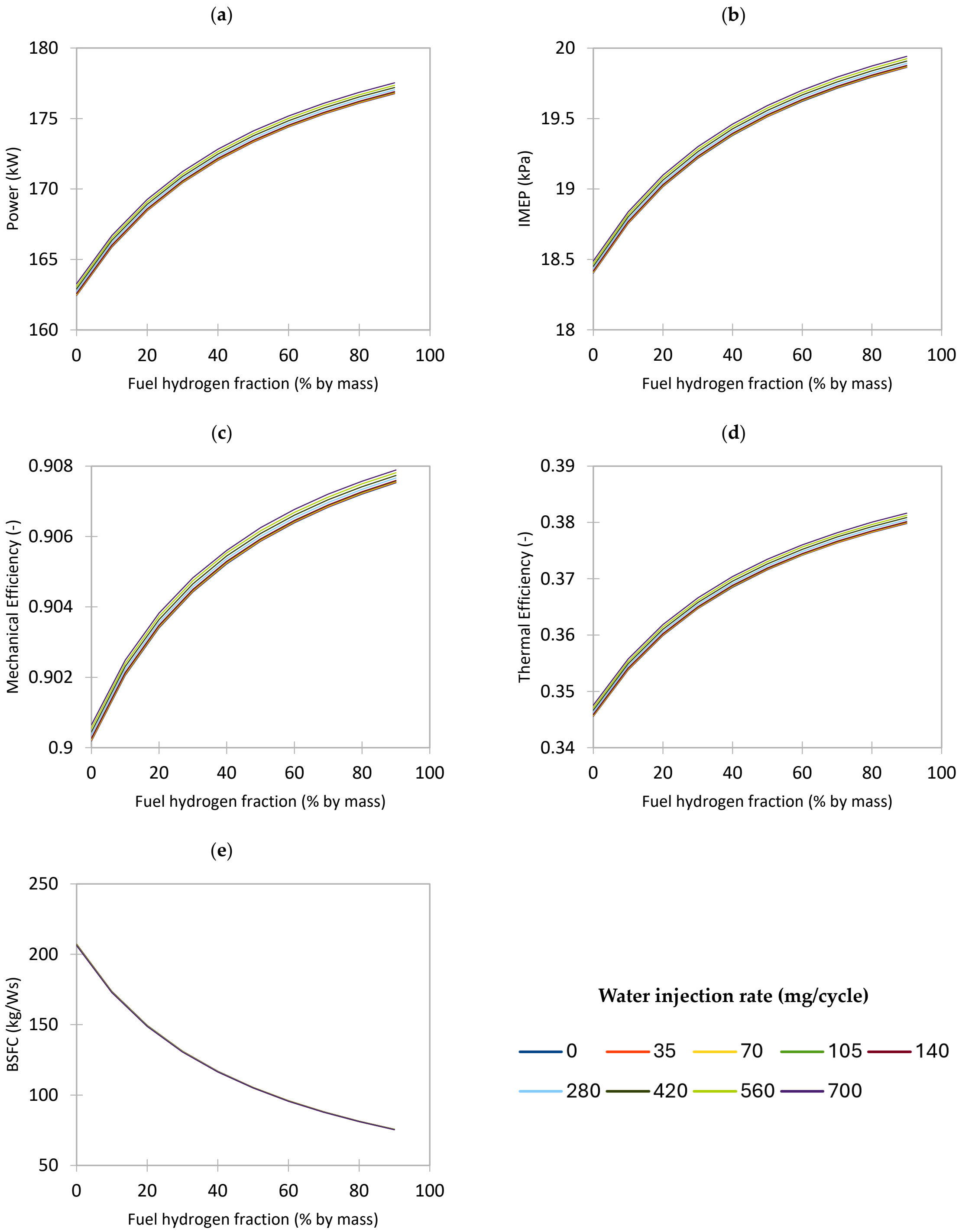

Figure 5. Simulated results showing the impact of water injection on diesel engine (**a**) power, (**b**) IMEP, (**c**) ME, (**d**) TE, and (**e**) BSFC at different hydrogen energy fractions.

3.1.2. Mechanical and Thermal Efficiencies

Figure 5c shows the effect of increasing hydrogen and water concentrations on the mechanical efficiency of the compression ignition engine. As discussed previously, hydrogen's higher diffusivity and flame speed contribute to the slight improvement in mechanical efficiency, which increased by approximately 0.8% in the highest hydrogen concentration case compared to neat diesel operation. Figure 5d shows the effect of increasing hydrogen and water concentrations on thermal efficiency. As observed with other performance metrics, increasing the hydrogen share improves performance. In terms of thermal efficiency, the gains are comparable to those seen in mechanical efficiency, with an increase of approximately 0.8% for the 90% hydrogen case relative to neat diesel operation. This improvement is primarily attributed to hydrogen's superior combustion characteristics, including its faster flame speed and higher diffusivity. Previous studies have demonstrated that hydrogen energy ratios between 10% and 50% yield higher efficiencies than neat diesel [6], and the results of this study confirm that the trend holds true across all tested energy ratios.

The injection of water had a negligible effect on mechanical efficiency. The 700 mg/cycle water case resulted in only a 0.05% improvement. This small gain could be attributed to the reduction in thermal stresses on engine components, which may lead to more consistent operation and lower internal friction [1]. This observation aligns with the existing literature, which suggests that water injection is expected to have minimal impact on performance and efficiency [13]. Water injection had a more noticeable, yet still negligible, effect on thermal efficiency compared to mechanical efficiency, resulting in approximately a 0.5% increase for the 700 mg/cycle case compared to the case without water injection. This can be attributed to the lower in-cylinder temperatures due to the vaporisation of water.

3.1.3. BSFC

Figure 5e illustrates the effect of increasing hydrogen and water concentrations on BSFC. Given that the calorific input into the engine remains constant, the BSEC is expected not to have a substantial change across all hydrogen cases. However, BSFC decreases significantly with hydrogen increase. For example, BSFC drops by approximately 63.5% in the 90% hydrogen case compared to the neat diesel engine. While this reduction appears significant, it aligns with the mass difference in injected fuel, which is 62.8% lower for the 90% hydrogen case, as shown in Table 4. Therefore, the reduction in BSFC is not only attributable to hydrogen's faster flame speed, high diffusivity, and high energy content but also to the lower fuel mass, though some improvement can be due to the superior characteristics of hydrogen [7].

Water injection's impact on BSFC is minimal, with an increase of only 0.5% observed for the 700 mg/cycle case when compared to the baseline results. It should be noted that in SI engines, WI has been shown to improve fuel consumption; however, in CI engines, WI leads to longer ignition delay, which largely cancels out this effect [12]. As a result, the slight reduction in fuel consumption due to water injection can be attributed to marginal improvements in efficiency and combustion pressures, but overall, these effects are consistent with the literature, which indicates that at high loads, water injection has no negative impact on BSFC [4,8].

3.2. Emissions

3.2.1. Carbon Oxides

Figure 6a,b shows the results of increasing the hydrogen and water concentrations in the compression ignition engine as it relates to CO and CO_2 emissions. As can be seen, the results of this study show that increasing the share of hydrogen decreases CO and CO_2 emissions. For example, the reduction can be up to 94% and 96% in CO and CO_2, respectively, for the 90% hydrogen case when compared to the engine running on neat diesel. As hydrogen is free of carbon atoms, the decreasing share of diesel fuel means fewer carbon atoms are available to form either CO or CO_2. However, as noted, the high diffusivity and flame speed, both of which reduce oxygen availability, as well as the higher combustion temperatures breaking down CO_2, are explanations as to why a measurable decrease of 1131.23 to 746.65 in the ratio of CO_2 to CO (indicating a reduction in diesel combustion quality) for increasing hydrogen shares can be seen. The reduction observed is generally in line with the literature, which states that for complete combustion, an 88% decrease in carbon emissions is expected for the 90% hydrogen case [6]. However, for the CO emissions, there are competing theories and evidence that claim that using hydrogen may either lead to an increase or a decrease. Adding hydrogen decreases the C/H ratio of the fuel [4,7], the high diffusivity of hydrogen promotes more complete combustion, and hydrogen can burn lean [4], all of which are reasons why CO emissions would be expected to reduce. However, port-injection of H_2, as well as the high flame speed of hydrogen and subsequent formation of H_2O, can decrease the amount of oxygen available in the combustion chamber to form CO_2, leading to increased CO levels. Additionally, the increased cylinder temperature can cause formed CO_2 to break down into CO and C. Finally, at high loads, CO may increase due to a lower oxygen concentration and faster reaction time, but this could be offset over the lifetime of the engine by increasing diesel concentration at low loads where fuel concentration is leaner and oxygen more abundant [4].

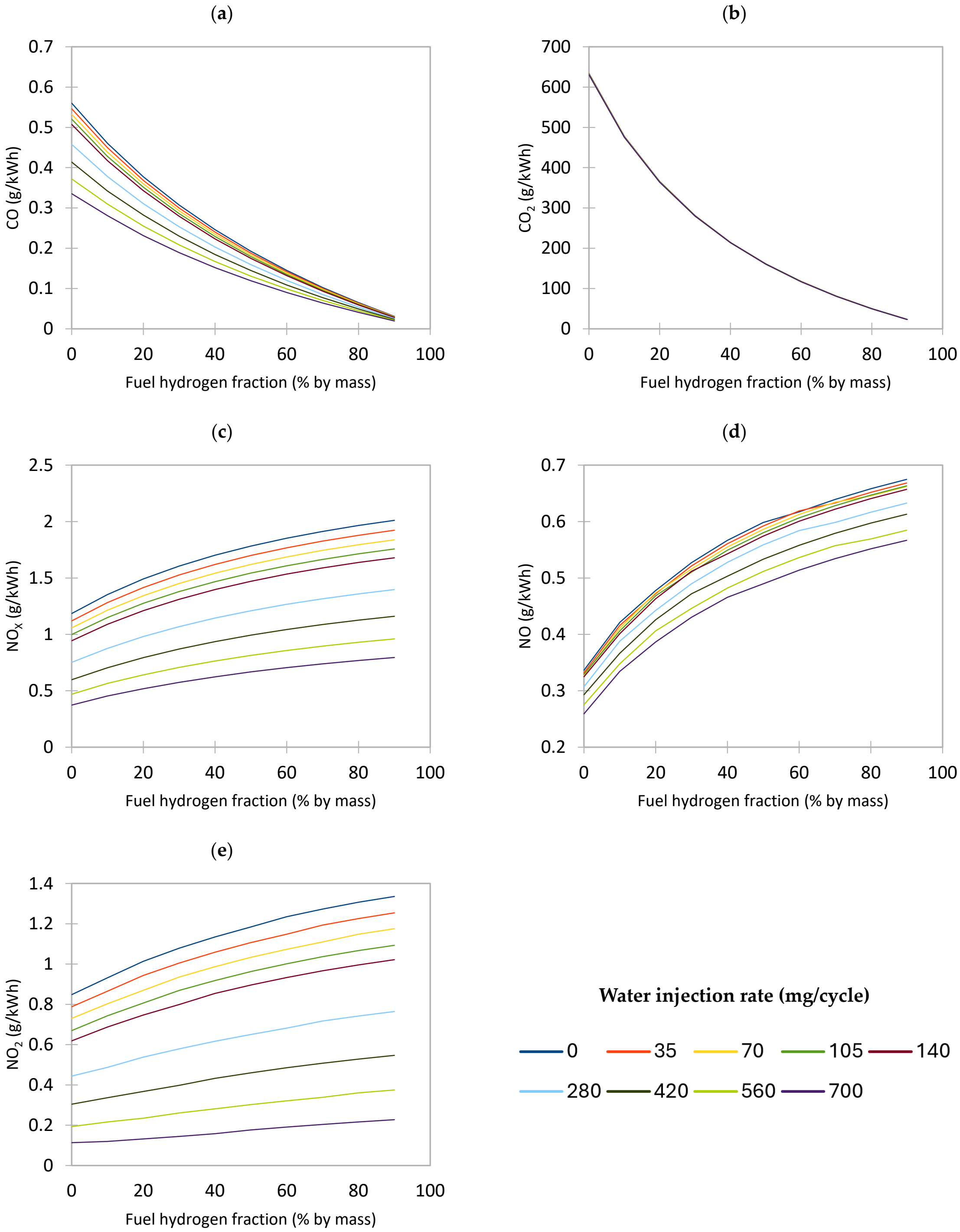

Figure 6. Simulated results showing the impact of water injection on diesel engine (**a**) CO, (**b**) CO_2, (**c**) NO_X, (**d**) NO, and (**e**) NO_2 at different hydrogen energy fractions.

Increasing the share of water also decreases the CO output by approximately 40% for the 700 mg/cycle case. The drop in CO emissions attributed to an increase in water injection might not be the result of water promoting more complete combustion, as Figure 6b shows almost no increase in CO_2 output for increasing water quantities. This may be an indication that the lower combustion temperatures afforded by water injection have produced a higher concentration of hydrocarbons, which is in line with the literature [1]. However, water injection has a negligible impact on CO_2 emissions (showing approximately a 0.4% decrease for the 700 mg/cycle case when compared to the baseline results), which correlates well with its impact on BSFC.

3.2.2. Nitrogen Oxides

The introduction of hydrogen fuel and water injection in compression ignition engines significantly impacts the formation of nitrogen oxides (NO_X), including nitric oxide (NO) and nitrogen dioxide (NO_2). Figure 6c–e shows the impact of increasing the hydrogen and water concentrations on nitrogen oxide emissions (NO_X, NO, and NO_2). It can be seen in Figure 6c that increasing the hydrogen content in the fuel mixture leads to a substantial rise in NO_X emissions. For example, the 90% hydrogen case resulted in a 70% increase in total NO_X emissions compared to the baseline diesel engine. The increase in NO emissions was particularly significant, with the 90% hydrogen case producing more than double the NO output of the unmodified engine. NO_2 emissions also increased with hydrogen addition, albeit less dramatically than NO. The 90% hydrogen ratio increased NO_2 by over 57% compared to neat diesel. This difference in NO and NO_2 formation rates can be explained by the complex chemical kinetics involved in NO_X formation and the specific conditions created by hydrogen combustion [30]. The observation in this study is consistent with existing research in the literature, which indicates that increasing hydrogen injection is associated with higher power, combustion temperatures, and elevated thermal NO_X production [4,6,7].

Adding hydrogen to the fuel mixture and reducing the amount of diesel decreases the fuel NOx [4]; however, the thermal NOx is the main contributor [9,10]. The rise in NO_X emissions with hydrogen addition can be attributed to several factors, such as higher combustion temperatures, since hydrogen combustion produces higher in-cylinder temperatures due to its rapid flame propagation and high energy content [31]. These elevated temperatures promote the formation of thermal NO_X through the Zeldovich mechanism. Another reason could be increased oxygen availability as hydrogen combustion leaves more oxygen available in the cylinder, facilitating NO_X formation [32]. The other reason could be the extended high-temperature duration, as the faster combustion of hydrogen prolongs the period of peak cylinder temperatures, allowing more time for NO_X formation [33]. This aligns with the trade-off between power and NOx emissions in internal combustion engines [4,6,7,34].

Water injection proved to be an effective method for reducing the elevated NOx emissions caused by hydrogen addition. The impact of water injection on NOx reduction was relatively consistent across different hydrogen ratios, resulting in an approximately 60–69% decrease in total NOx emissions over the range of 0–90% hydrogen energy. This agrees with the literature, which states that NO_X in diesel engines can be reduced by 60–70% with WI without significant adverse effects on power, economy, or soot production [12,13]. It should be noted that this reduction is comparable to the 63.1% decrease found by Liu et al. when employing a 15% EGR rate as opposed to water injection [15]; however, it does not suffer the same power reduction as a result. The effect on NO_2 was even more pronounced, with water injection capable of an 82.95–87.18% reduction in NO_2 emissions for the 700 mg/cycle condition compared to zero water injection. The effectiveness of water injection in reducing NO_X emissions can be explained by several mechanisms. For example, charge cooling, in which water injection lowers the intake charge temperature and reduces peak combustion temperatures and thermal NO_X formation [9]. Furthermore, the presence of water vapour in the combustion chamber dilutes the oxygen concentration, inhibiting

NO_X formation [33]. The other reason could be the chemical effects, as water molecules participate in chemical reactions that compete with NO_X formation pathways [1,2,10,35].

Interestingly, the combination of hydrogen addition and water injection resulted in cases where NO_X emissions were lower than the baseline diesel without hydrogen and water injection. For instance, the 10% hydrogen, 700 mg/cycle water case produced lower NO emissions than the baseline diesel engine. These findings are consistent with the recent literature. Xu et al. [33] reported that direct water injection could reduce NO_X emissions by up to 70% in a hydrogen-fueled SI engine. Similarly, Alrazen et al. [36] observed NOx reductions of up to 68% with water injection in a hydrogen/diesel dual-fuel engine. It is worth noting that while intake manifold water injection (IMWI) was used in this study, it may not be the most efficient method, as manifold and port WI results in difficulties in achieving precise control over injection times and quantities, which can lead to less than the maximum possible NO_X reduction [1], as well as wall-wetting, which can cause increased emissions and wear, particularly during cold starts [12]. Direct water injection (DWI) or in-cylinder injection could potentially offer greater NO_X reduction and better control over injection timing and quantities. However, in practice, IMWI or port-injected water is more common than DWI or fuel emulsification [2] because it is cheaper and easier to implement [12].

4. Implications, Limitations, and Further Work

The results of this study show that an H_2DDI engine with WI is most suitable for stationary applications due to the volumetric requirements of storing hydrogen for use as a combustible fuel. Table 5 shows the fuel volume requirements for hydrogen and diesel per hour of engine operation at full load, 2000 rpm.

Table 5. Fuel consumption rates at 2000 rpm.

Hydrogen Percentage (by Mass)	Diesel Fuel Consumption (L/h)	Hydrogen Fuel Consumption (L/hr)	
		25 °C/ 700 bar	−253 °C (Liquid H_2)
0	66.00	0.00	0.00
10	50.84	121.25	67.77
20	39.50	211.94	118.46
30	30.69	282.34	157.81
40	23.66	338.57	189.24
50	17.91	384.52	214.92
60	13.13	422.77	236.30
70	9.09	455.11	254.37
80	5.62	482.81	269.86
90	2.62	506.80	283.26

According to Table 5, the Cummins engine may operate for one hour and consume 66 L of neat diesel. Running on 90% hydrogen, the engine requires only 2.62 L of diesel per hour; however, it requires just above 283 L of hydrogen if it is stored in liquid form or 506 L of hydrogen if stored in gaseous form.

The storage space to house such fuel quantities is likely only feasible in stationary engine applications, and vehicles would be limited to much lower hydrogen energy fractions. However, in smaller, more efficient engines such as those applicable for use in passenger vehicles, the fuel requirements would be lower, and higher hydrogen concentrations might be considered. Additionally, automotive engines do not typically spend significant time at full load, so real-world consumption figures in this application would likely not be as high.

Automotive applications also need to consider transient engine operations, cold start conditions, and other challenges, such as thermal management, all of which are not considered in the steady-state test case employed by this paper. Future works would benefit from studying the effects of hydrogen and water at varying loads and speeds. Additionally, automotive applications would benefit from emerging hydrogen storage technologies such as cryo-compressed hydrogen (CcH_2) storage, which can increase the energy density of hydrogen by volume beyond that of 'conventional' liquid hydrogen [37], or liquid organic hydrogen carriers, which may ease the process of transporting and storing hydrogen fuels using existing processes and infrastructure [38].

Similar to Table 5, the water requirements for the injection rates considered in this study are shown in Table 6. Again, the higher water injection rates may be most suitable in stationary applications; however, the application of DWI and studies on ideal injection timing may reduce the quantity of water required to achieve similar results, and this may be an area for future studies.

Table 6. Investigated water consumption rates.

Water Injection Rate (mg/cycle)	Water Consumption (L/h)
0	0
35	2.09
70	4.19
105	6.28
140	8.37
280	16.75
420	25.12
560	33.5
700	41.87

It is noted that the effect of increasing hydrogen energy fractions on engine performance and emissions appears consistent, and there are no irregularities that warrant further investigation at closer intervals.

The water injection rates employed by this study correspond to 0%, 12.5%, 25%, 37.5%, 50%, 100%, 150%, 200%, and 250% water by mass compared to the fuel rate of the baseline engine. Initially, only increments of 50% were tested. However, preliminary findings revealed that lower injection rates had a significant impact on engine performance and emissions, prompting further exploration of intermediate values within this range.

The long-term effects of hydrogen and water injection also need to be considered. A study has shown that prolonged use of neat hydrogen as a fuel has some adverse effects on the durability of existing engines, particularly due to hydrogen embrittlement of valves and valve seats. Though it was not observed during the experimental testing, this embrittlement could have led to premature engine failure [39]. The study suggests that future works should investigate alternative materials for these components that might be less susceptible to this issue. Similarly, González et al. [40] detail the methods by which hydrogen embrittlement has been shown to affect standard engine components and suggest the use of aluminium alloys due to their lower permeability. Additionally, it is suggested that the use of water injection may lead to corrosion, especially in the presence of sulfur found in diesel fuel [8]. It may also lead to increased friction and/or blow-by oil dilution. However, there are insufficient studies in the literature to properly gauge the lifetime likelihood and impact of these effects [1].

In summary, future works should aim to address transient engine conditions, direct water injection, investigations on ideal injection timing of both hydrogen and water, the effects of water injection on knock suppression in HDDF engines, and the long-term effects of hydrogen and water injection on engine durability, as these metrics could not be determined by the methodology employed in this study.

5. Conclusions

This study investigated the performance and emissions of an H_2DDI engine with water injection. The engine model was validated experimentally and tested across a range of hydrogen ratios between 0 and 90%, where the input calorific energy was held constant and a range of water injection rates between 0 and 700mg/cycle. The power, IMEP, mechanical and thermal efficiencies, BSFC, CO, CO_2, NOx, NO, and NO_2 emissions were measured. The results showed modest improvements in thermal and mechanical efficiencies and an approximate power output increase of 8.8% across the hydrogen energy ratios and 0.5% across the water injection rates. BSFC also improved.

CO and CO_2 emissions were reduced by 94% and 96%, respectively, as a result of the 90% hydrogen share. A 40% decrease in CO was observed for the 700 mg/cycle water injection rate, though water had a hardly measurable effect on CO_2. NO and NO_2 emissions increased by over double their baseline values as a result of the 90% hydrogen share, though they decreased again by approximately 20% and 85%, respectively, as a result of water injection. While hydrogen addition significantly increases NOx emissions due to higher combustion temperatures and altered combustion characteristics, water injection proves to be an effective countermeasure. The combination of hydrogen fuel and water injection can potentially lead to reduced NOx emissions compared to conventional diesel engines, offering a promising pathway for cleaner combustion in dual-fuel engines.

The results indicate both that hydrogen/diesel mixture injection in diesel engines is a viable method of mitigating carbon emissions and reducing reliance on fossil fuels by employing existing technologies and infrastructure and that water injection is a viable method for reducing the otherwise inevitable NO_X increases that these engines have historically been associated with. However, the low energy density of hydrogen by volume and the relatively large quantities of water injected will significantly impact the applications of these findings outside of stationary engines.

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