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Effect of Water Injection on Combustion and Emissions Parameters of SI Engine Fuelled by Hydrogen–Natural Gas Blends

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Abstract: Technologies used in the transport sector have a substantial impact on air pollution and global warming. Due to the immense impact of air pollution on Earth, it is crucial to investigate novel ways to reduce emissions. One way to reduce pollution from ICE is to use alternative fuels. However, blends of alternative fuels in different proportions are known to improve some emissions' parameters, while others remain unchanged or even worsen. It is therefore necessary to find ways of reducing all the main pollutants. For SI engines, mixtures of hydrogen and natural gas can be used as alternative fuels. The use of such fuel mixtures makes it possible to reduce CO, HC, and CO_2 emissions from the engine, but the unique properties of hydrogen tend to increase NO_x emissions. One way to address this challenge is to use port water injection (PWI). This paper describes studies carried out under laboratory conditions on an SI engine fuelled with CNG and CNG + H_2 mixtures (H_2 = 5, 10, 15% by volume) and injected with 60 and 120 mL/min of water into the engine. The tests showed that the additional water injection reduced CO and NO_x emissions by about 20% and 4–5 times, respectively. But, the results also show that water injection at the rate of 120 mL/min increases fuel consumption by between 2.5% and 7% in all cases.

Keywords: hydrogen; natural gas; water injection; spark ignition engine; in-cylinder pressure

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1. Introduction

Human economic activity increases atmospheric heat pollution, increasing concentration of greenhouse gases (GHG) which increases the natural greenhouse effect and contributes significantly to the rise in global average temperatures [1]. Most GHGs are produced by burning fossil fuels in industrial, transportation, and agricultural production processes, and many are emitted from waste [2].

One of the European Union's documents states that GHG emissions from road transport and shipping should be further limited, taking into account the international dimension, and that lifecycle CO_2 emissions from transport fuels should be reduced by accelerating the development of sustainable biofuels, particularly second-generation biofuels [3].

Road transportation is a significant contributor to air pollution, which adversely affects human health and the environment. Vehicles emit various pollutants, including nitrogen oxides (NO_x) and particulate matter (PM). [4]. NO_x is a combination of nitrogen dioxide (NO_2) and nitrogen oxide (NO). NO_2 is a toxic gas that causes 79,000 premature deaths each year in Europe. In the atmosphere, NO is converted to NO_2 and contributes to the formation of the ozone (O_3). NO_x emissions also lead to the formation of secondary particles in the air and contribute to acidification and eutrophication, which inflict serious harm on ecosystems. Road transport is responsible for one third of NO_x emissions and is the dominant source in urban areas with heavy traffic [5]. Vehicle pollution is particularly high during engine start-up, when increased amounts of fuel or enriched flammable mixtures are required [6].

Generally speaking, road transport is the main source of EU NO_2 emissions, while commercial, institutional and residential fuel combustion contribute the most to total primary PM emissions, especially in some Eastern European countries [7,8].

Rising global air pollution is forcing scientists, politicians, and manufacturers to take immediate action to reduce environmental pollution and the effects of climate change. Several of the most popular alternative fuels are currently being identified, including ethanol, methanol, methane, compressed natural gas (CNG), and hydrogen, which can be used in the transportation sector [9]. However, all of them have some disadvantages as well as advantages.

One of the most promising fuels is hydrogen. It is a fuel with extremely high burning velocity, low energy for ignition, and a low quenching gap, which improves the combustion process even in the presence of a lean mixture [10,11]. Under stoichiometric conditions, hydrogen laminar flame speeds are about five times higher than those of methane [12]. If the energy of water electrolysis is provided from renewable energy sources, hydrogen production is a sustainable process without GHG emissions.

Hydrogen has a much wider range of flammability in the air than methane, propane, or gasoline, and minimal ignition energy. The minimum burn energy is usually for mixtures near the stoichiometric composition, but at low flammability limits, hydrogen heat energy is similar to that of methane (Figure 1) [13].

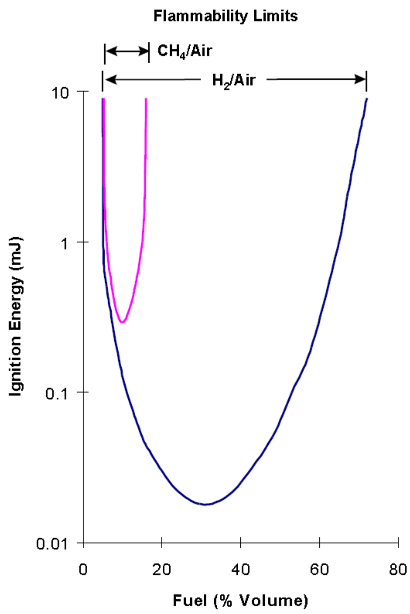


Figure 1. Minimum ignition energies [13].

Hydrogen's minimum autoignition temperature (585 °C) is higher than that of methane (540 °C), propane (487 °C), and gasoline (228–471 °C) [12,14]. Hydrogen flames differ from hydrocarbon flames, with little or no soot formation, and the heat generated by the flame itself is warmer than hydrocarbon flames [14]. Hydrogen also has good thermal efficiency [9].

The main reaction of hydrogen combustion is:

$$2H_2 + O_2 \rightarrow 2H_2O, \tag{1}$$

therefore, the combustion of pure hydrogen in the internal combustion engine does not produce CO_2, CO, or HC, and the only toxic compound emitted is nitrogen oxides (NO_x), which are formed due to the extremely high combustion temperature. The combustion temperature of hydrogen, although lower than that of gasoline, is higher than that of methane [10], so the NO_x emission of a hydrogen-powered engine should theoretically be higher when comparing NO_x emissions with natural gas engines.

Adding even a small amount of 3–7% hydrogen and oxygen to a gasoline engine increases the brake power by 10–12% over pure gasoline and improves the thermal efficiency of the engine. The addition of hydrogen can also dramatically reduce HC emissions, especially in the medium to high-speed range. The CO emissions at all engine speeds have improved significantly. One of the main disadvantages of adding hydrogen is the increase in NO_x emissions; NO_x emissions increased by 94.7–129.5%, and 106.6–141.1%, respectively, accompanied by 3.75–7.5% of hydrogen additions [15].

However, it is very difficult to control the combustion process of hydrogen due to its high burning rate, reactivity, and low methane number [11]. In addition, due to its low density, hydrogen has a very high volume (compared to other fuels), which makes it quite challenging to use as a pure fuel in internal combustion engines, making it much more rational to use as an additive in other fuel blends [16,17].

One of the more efficient ways to use hydrogen in internal combustion engines is to mix it with different gases [12,18–20]. In order to improve the efficiency of natural gas engines and promote hydrogen technologies and markets, hydrogen can be added to natural gas and a mixture of hydrogen and natural gas can be produced, usually called HCNG. The hydrogen additive typically makes up 5–30% of the fuel by volume. The main parameters of the combustion process are shown in Table 1.

Table 1. Comparison of the main parameters of natural gas and natural gas with hydrogen additive (HCNG) [20].

Parameter	Natural Gas	10%(vol.)H_2 + NG (HCNG10)	20%(vol.)H_2 + NG (HCNG20)	30%(vol.)H_2 + NG (HCNG30)
H_2, % (energy share)	-	3.2	7.0	14.4
Lower heating value, MJ/kg	45.3	46.2	46.7	48.5
Lower heating value, MJ/Nm^3	36.9	34.3	31.7	29.2
Air-to-fuel ratio	15.6	15.8	16.1	16.4

As can be seen from the data presented, the net calorific value of the fuel increases as the hydrogen content increases. The HCNG blend releases more heat accordingly, by 2% (HCNG10), 3% (HCNG20), and 7% (HCNG30). Due to the higher amount of heat, higher engine power and other efficiency indicators can be generated [21].

The methane–hydrogen mixture stoichiometric reaction equations are as follows:

$$(\alpha\ CH_4 + \beta\ H_2) + (2\ \alpha + \beta/2)(O_2 + 3.76\ N_2) \rightarrow \alpha\ CO_2 + (2\ \alpha + \beta)\ H_2O + (2\ \alpha + \beta/2)\ 3.76\ N_2 \quad (2)$$

where $\alpha + \beta = 1$. The α and β amounts represent molecular composition for each blend, and it is immediately observed that the reduction in C/H ratios leads to the theoretical reduction of CO_2 compared to pure methane [20].

Hydrogen laminar combustion rate is about eight times higher than methane and it reduces combustion time when mixed with natural gas at low concentrations. Hydrogen greatly increases the lean limit, reduces combustion time, and improves thermal efficiency [22]. Studies have shown that the use of such mixtures reduces most pollutants, except NO_x [21]. Benchmark studies have also shown that engine efficiency (power, fuel consumption) has improved slightly [23]. However, the number of toxic NO_x emissions have increased considerably [20,22].

One of the most effective ways to reduce NO_x emissions is to lower the combustion temperature. Currently, car and engine manufacturers reduce the combustion temperature by using one of the most popular measures, the EGR system [24–26]. However, the EGR system has certain drawbacks that significantly affect engine durability and performance. James W. Heffel, a scientist at the University of California, studied the NO_x emissions of hydrogen-fuelled internal combustion engines using EGR. He found that while using the EGR strategy, the engine torque is significantly reduced [27].

These reasons encourage the use of other ways to reduce the combustion temperature. One such method is to inject water into the engine cylinders [28]. Water injection (WI) is a system used during World War II to delay the detonation of aircraft. The injected water cools the combustible mixture, thus reducing the pressure in the cylinder and preventing detonation.

Chinese and British scientists [24] found that the wall film formation, which reduces charge cooling and premature vaporisation outside the cylinder, is the main reason for reducing the efficiency of the introduction of port water injection, compared to direct or emulsified water injection. Efficient water evaporation evaluations show the importance of designing and optimizing WI systems and accurately calculating heat release speeds. WI can be used as an effective alternative to EGR to introduce inert species into cylinders to mitigate the knock of SI engines and reduce the NO_x emissions of CI engines [24].

With regular gasoline, the injected water absorbs some of the energy as it evaporates, reducing the maximum pressure and temperature in the cylinder [29]. In SI engines, WI slows down the speed of the laminar flame mainly, but combustion duration does not have a significant impact when combined with advanced spark timing and a small amount of injected water. The effect of WI on combustion emissions in SI should be taken into account, in addition to engine operating conditions and adjustment of other parameters, such as ignition timing and AFR. Increased water flow and fuel enrichment reduction simultaneously reduce HC and CO, but under stoichiometric operating conditions, the trend for WI is different. Changes in NO_x and PM emissions also depend on both the amount of injected water and the air–fuel ratio in the cylinders [24].

Researchers at the Indian Institute of Technology, Madras, studied pure hydrogen-powered SI engines, and found that the brake torque increased slightly with WI. However, it has been observed that the indicated mean effective pressure (IMEP) remains the same as for WI. Therefore, increased torque may be due to a slight reduction in friction losses. Water reduces the maximum cycle temperature and significantly reduces NO emissions to 70%. Analysis of cylinder pressure changes shows that the exhaust pressure increased with WI, due to slow combustion. WI also slightly increases the peak pressure fluctuations. This may be due to the reduction in the rate of combustion, due to the effect of water dilution [30].

The use of hydrogen as an additional fuel reduces NO_x emissions from SI gasoline engines ($H_2 + O_2$) with WI and improves engine performance. NO_x emissions increased by 94.7% to 129.5% and 106.6% to 141.1%, respectively, with the addition of 3.75% of hydroxygen and 7.5% of hydroxygen. This huge increase in NO_x emissions was reduced due to water pulverisation. However, NO_x emissions of 3.75% hydrogen and water pulverization, and 7.5% hydrogen and water pulverization increased by 45.3% to 70.2% and 54.9% to 87.2%, respectively, compared to gasoline [15].

WI affects combustion in the following aspects: (1) the injection start (SOC) delays between one and two crank angles; (2) the process is less abrupt, and (3) the difference in the peak pressure of the cylinder or the indicated power is generated. Since the maximum quantity of water supplied was high to ensure combustion stability and NO_x control, industrial technologies have evolved to recover exhaust water by condensation and reuse it into engines [31].

WI is a cost-effective approach for smaller gasoline engines that operate without fuel enrichment (Lambda = 1), and the water–fuel ratio required for the stoichiometric operation depends on the implementation of water injection, driving cycles, and engine specifications. In regard to the cooling of the inside cylinder, the direct inside cylinder WI is the best option for the same amount of water, and the port WI is better than the upper WI. The pressure of the injection, the time of injection, and the location of the water should be optimized, taking into account combustion, water evaporation, and emissions. In addition, it is important to consider the selection of WI implementations in terms of costs and other benefits [24].

Together with high compression ratios, multi-stage superchargers, or Miller cycles, the WI on SI engines has significant potential to further reduce CO_2 emissions and has been shown to be a cost-effective solution for the SI engines of the new generation. Reduced turbine entry temperature can be used as a catalyst for using variable geometry turbines on gasoline engines, and reduced thermal stress can reduce the material costs of turbochargers [24].

As air temperature is crucial to fully evaporate water, this suggests that water must evaporate within cylinders and must be evaporated in a cylinder with temperatures much higher than in the intake system or ports. Direct WI solutions are preferred to achieve the most flexible and efficient water operation. This type of injection faces cost limitations and reliability issues due to the large thermal load that the injectors are facing every time on shut down. In the case of port WI solutions, the time of injection should promote water evaporation in the cylinder [32]. Port water injectors can be combined with direct water injectors, or direct water injectors together, to provide the best solution for the design of new devices. Direct injections do not affect the density of air entering the cylinder, but allow water to be introduced before, during and after combustion. This can reduce heat losses and increase steam expansion [33].

A detailed analysis of the literature has shown that no experimental research has been conducted with an SI engine running on a natural gas–hydrogen mixtures (hydromethane) with water injected into the engine cylinders. Therefore, this paper deals with the combustion of hydromethane using a port water injection (PWI) solution to improve the efficiency and ecological parameters of the SI engines and to investigate the stability and reliability of the combustion. PWI was chosen to avoid the thermal load of the injector, and to provide conditions for better evaporation of water, starting the evaporation process already in the intake manifold. In our subsequent studies, it was observed that direct water injection impairs the evaporation of water and promotes the penetration of water in the engine oil. And it has also been noted that constant cooling of the injector and constant water spraying is necessary, even when it is not useful at all, for example at low engine loads.

2. Materials and Methods

2.1. Research Methodology

This experimental research was performed in the laboratory of the enterprise SG dujos Auto. Four different types of gas mixtures were chosen for the research:

(a) pure natural gas (CNG);
(b) natural gas with 5% (v/v) hydrogen additive (5% H_2 + CNG);
(c) natural gas with 10% (v/v) hydrogen additive (10% H_2 + CNG);
(d) natural gas with 15% (v/v) hydrogen additive (15% H_2 + CNG).

Experimental tests are performed at a fixed traction load of P_t = 35 kW and at fixed engine speeds of n = 3000 rpm.

Two different water injection flows were chosen for the selected engine operating modes, based on literature source analysis: 60 mL/min (3.6 kg/h) and 120 mL/min (7.2 kg/h).

During the experimental study, the main ecological and efficient engine indicators are registered.

2.2. Equipment and Tools for Experimental Research

Figure 2 shows a diagram of the test equipment. Additional gas cylinders outside the vehicle were used for testing.

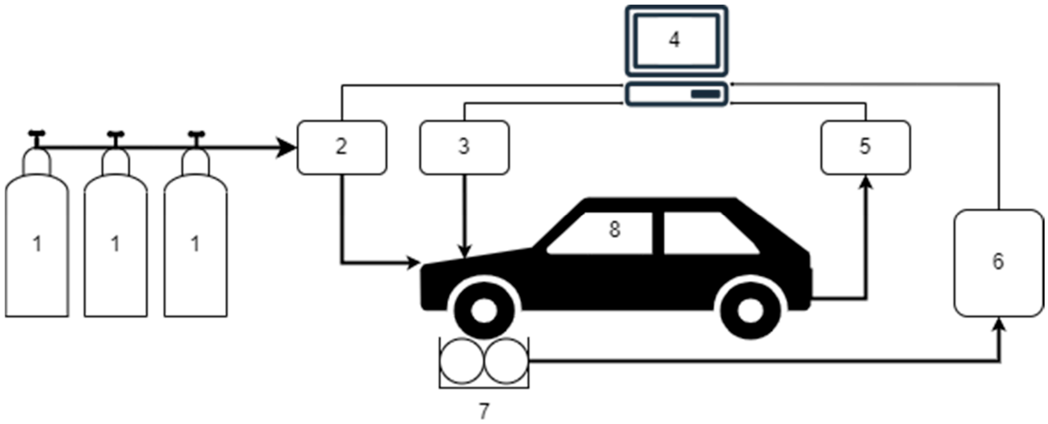


Figure 2. Test scheme: (1) cylinders of gas mixtures; (2) flow meter, *Rheonik RHM 015*; (3) water injection system, *AEM 30-3000*, (4) data logging system, *DAS*; (5) exhaust gas analyser, *OPUS 40–D*; (6) control unit of traction stand, *VT-4/B2 Modular Dynamometer*; (7) rolls of the traction stand, (8) test car.

2.2.1. Test Car

The Volkswagen Caddy EcoFuel, which runs on compressed natural gas, is being used for experimental research. The gas storage cylinders for this car are located at the rear of the car, by the wheel axle. There is also a small tank for petrol. The main technical data of the test vehicle are given in Table 2.

Table 2. Technical data of Volkswagen Caddy EcoFuel.

Parameter	Value
No. of cylinders	4
Engine displacement, cm^3	1984
Bore, mm	82.5
Stroke, mm	92.8
Number of valves	8
Compression ratio	13.5:1
Power, kW (at rpm)	80 (5400)
Torque, Nm (at rpm)	160 (3500)
Fuel	Compressed natural gas/petrol RON98
Fuel consumption (CNG), kg/100 km: urban/extra urban/combined	8.2/4.7/6.0
Emission requirements	EU4

2.2.2. Water Injection System

A reconstructed *AEM 30-3000* (Advanced Engine Management Inc., Hawthorne, CA, USA) water injection system was used in the experimental research. This system delivers the amount of water as a function of the pressure in the intake manifold, but has been redesigned to allow the amount of water sprayed to be selected as required. The system was modified using the Optima electronic control unit, the software that allows the desired nozzle opening time to be selected for each cycle when the intake valve is opened. Hydromethane was supplied via gas injectors and water via petrol injectors fitted by the car manufacturer.

2.2.3. Gas Flow Meter

Natural gas and hydromethane were measured using a Coriolis mass flow meter. The fuel flow meter was a *Rheonik RHM 015* (Rheonik, Odelzhausen, Germany) (Table 3), which was connected to the high-pressure fuel supply system upstream of the gas reducer, which reduced the gas to 1.5 bar.

Table 3. Parameters of gas flow meter *Rheonik RHM 015*.

Parameter	Value
Fuel state	Gas and liquid
Measuring type	Coriolis mass flowmeter
Measuring range	0.004 . . . 0.6 kg/min
Accuracy	±0.10%
Repeatability	±0.05%

2.2.4. Gas Analyser

Exhaust emissions were measured using an *OPUS 40-D* (Opus Prodox AB, Mölndal, Sweden) exhaust gas analyser when hydromethane was tested (Table 4). The analyser had the ability to change the measurement mode according to the fuel being tested. During tests where the fuel mixture has a CH_4 as the main base element, the analyser was switched to the natural gas fuel measurement mode.

Table 4. Parameters of exhaust gas analyser *OPUS 40–D*.

Parameter	Measuring Range	Accuracy ±rel. and (±abs)
CO	0 . . . 10, % vol.	0.02% (3%)
CO_2	0 . . . 20, % vol.	0.3 (3%)
HC	0 . . . 2 000, ppm	4 ppm (3%)
NO_x	0 . . . 5 000, ppm vol.	-
O_2	0 . . . 25, % vol.	0.02% (1%)
λ	0.6 . . . 1.7	-

2.2.5. Dynamometer

Experimental research was performed by simulating smooth running conditions on a traction stand *VT-4/B2 Modular Dynamometer* (Vtech Tuning EU sp. z o.o., Kraków, Poland) (Table 5).

Table 5. Technical parameters of dyno stand *VT-4/B2 Modular Dynamometer*.

Parameter	Value
Type of brakes	eddy current
Brake torque, Nm	3200
Dimensions of rolls, mm	5500 × 3800
Max. axle load, kg	3000
Max. vehicle speed, km/h	300
Max. traction power, kW	540

2.2.6. Data Logging Software

All test data were recorded using self-created software–DAS-01 (SG dujos Auto, Pabradė, Lithuania), which collects data from the gas analyser, gas flow meter, traction bench, and indicators from the engine control unit via the OBDII interface. This software was developed by the employees of enterprise SG dujos Auto to simplify the registration of various incoming data.

2.2.7. Numerical Modeling

The AVL BOOST numerical simulation software was used to model the engine work cycles while the engine was working on CNG and CNG + H_2 mixtures and injecting 60 and 120 mL/min of water. The preparation of the fuel mixture is selected directly in the cylinder. AVL BOOST (AVL, Graz, Austria) software can be used to model the thermodynamic processes of the engine during combustion in the cylinder. The modelling of the thermodynamic state of the cylinder is based on the first law of thermodynamics:

$$\frac{d(m_c \cdot u)}{d\varphi} = -p_c \cdot \frac{dV}{d\varphi} + \frac{dQ_F}{d\varphi} - \sum \frac{dQ_w}{d\varphi} - h_{BB} \cdot \frac{dm_{BB}}{d\varphi} + \sum \frac{dm_i}{d\varphi} \cdot h_i - \sum \frac{dm_e}{d\varphi} \cdot h - q_{ev} \cdot f \cdot \frac{dm_{ev}}{dt}; \quad (3)$$

where $\frac{d(m_c \cdot u)}{d\varphi}$ is the change of the internal energy in the cylinder; $p_c \frac{dV}{d\varphi}$ is piston work; $\frac{dQ_F}{d\varphi}$ is fuel heat input; $\sum \frac{dQ_w}{d\varphi}$ is wall heat losses; $h_{BB} \frac{dm_{BB}}{d\varphi}$ is enthalpy flow due to blow-by; m_c is mass in the cylinder; u is specific internal energy; p_c is cylinder pressure; V is cylinder volume; Q_F is fuel energy; Q_w is wall heat loss, and φ is crank angle.

The parameters of the combustion process are modelled using the Vibe function, where the shape parameter m_v indicates the intensity of combustion. The rate of heat release depends on its magnitude. The lower the value of the parameter, the more intense the heat release at the start of combustion (Figure 3).

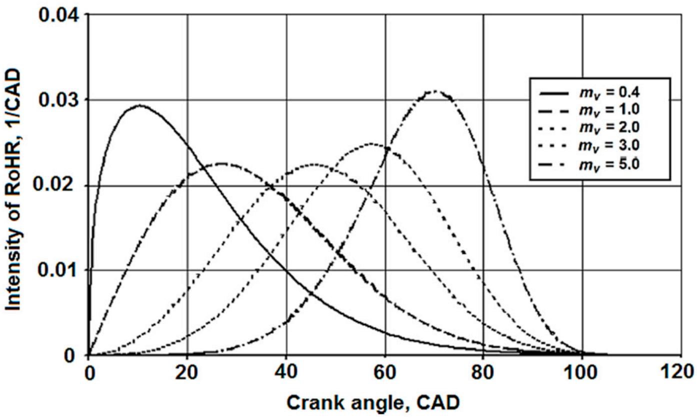


Figure 3. The dependence of rate of heat release on different combustion intensity shape parameter *mv*.

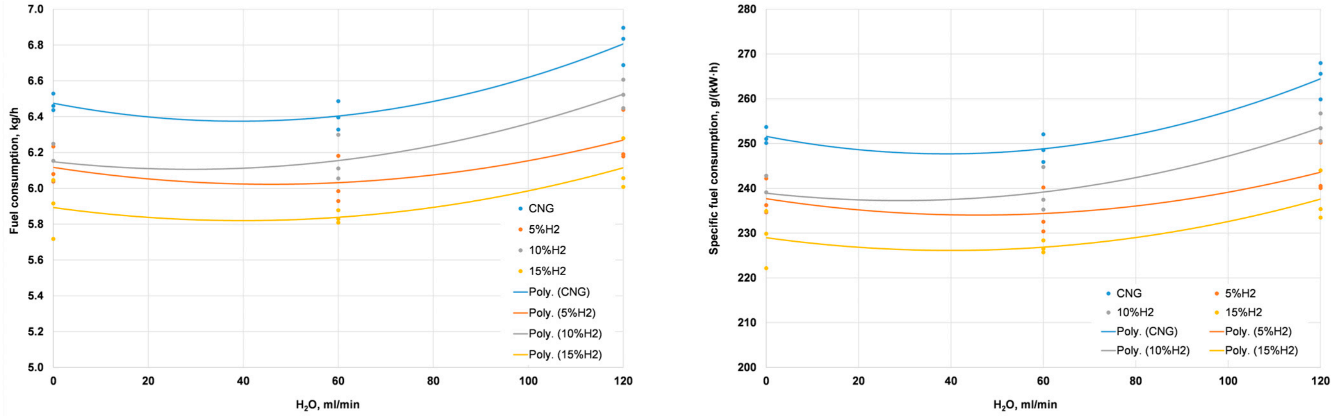
In the modelling of the combustion of CNG and CNG + H_2 mixtures and injection of 60 and 120 mL/min of water, a two-zone Vibe function is used to approximate the heat release intensity. The two-zone Vibe divides the cylinder into two parts and evaluates the heat release from the burned zone and the unburned zone of the mixture.

3. Results and Discussion

3.1. Experimental Research

During the experimental research, the influence of water content on the engine combustion process was investigated using four different fuels (CNG, 5%H_2, 10%H_2, and 15%H_2) to study ecological and energy indicators.

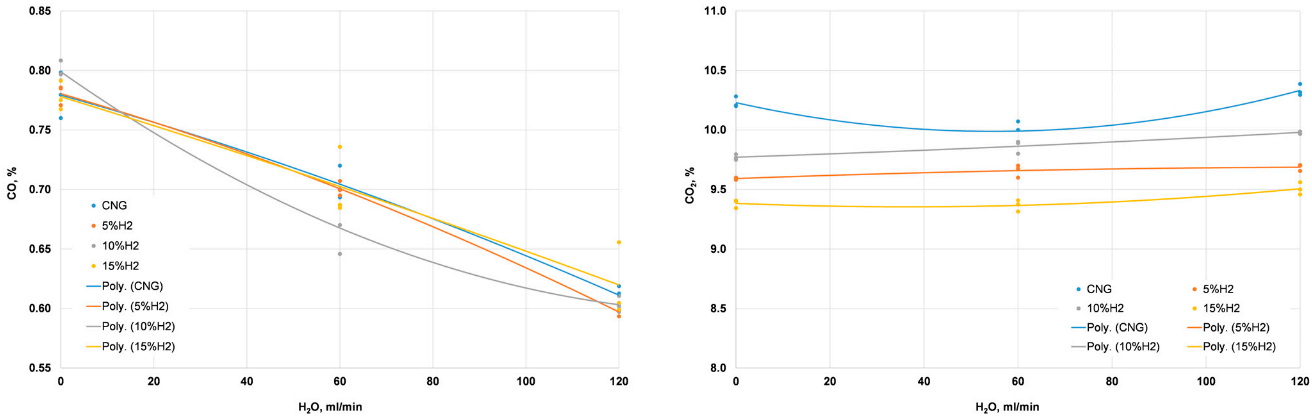
The hourly fuel consumption of the engine is shown in Figure 4a. When water is not injected into the engine's intake air, the H_2 additive reduces fuel consumption by 5 to 9%. At a 60 mL/min water spray volume, the H_2 additive reduces fuel consumption by 3 to 9%, and by 3 to 10% at 120 mL/min. This is because hydrogen has very good combustion properties and thermal efficiency, and even a small amount of hydrogen can improve engine efficiency [34,35]. The figure also shows that 60 mL/min injected water reduces fuel consumption insignificantly (0.5 . . . 1.5%), but water injection at the rate of 120 mL/min increases fuel consumption by between 2.5% and 7% in all cases. It is possible that this increase is due to over-inhibition of combustion by water, which has to be compensated by increasing the fuel injection [35,36]. The analysis of the specific fuel consumption in Figure 4b shows very similar trends.



(**a**) (**b**)

Figure 4. Effect of water injection on fuel consumption when the engine runs on different fuel mixtures: (**a**) hourly fuel consumption, (**b**) specific fuel consumption.

The results in Figure 5a show that the additional use of hydrogen together with natural gas does not have a significant effect on the amount of carbon monoxide in the engine exhaust gas because, in the case of this study, hydrogen only minimally increases the combustion temperature.



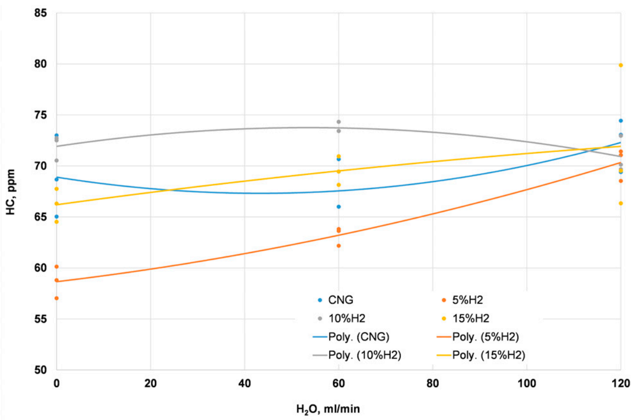
(**a**) (**b**)

Figure 5. Effect of water injection on CO and CO_2 when the engine runs on different fuel mixtures: (**a**) CO dependences, (**b**) CO_2 dependences.

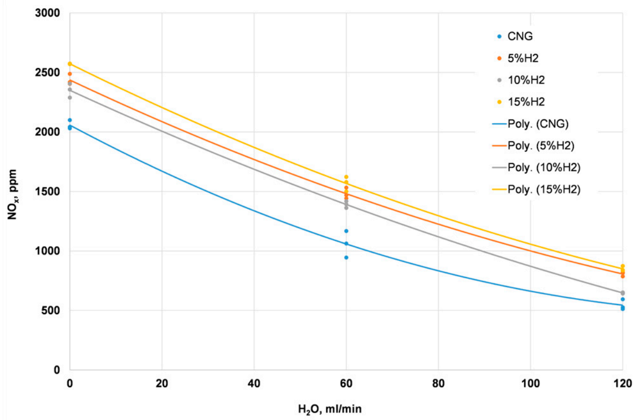
From Figure 5a, it can be seen that when the water injection into the cylinders is continuously increased from 0 to 120 mL/min, less CO was continuously generated (about 25 percent in total). The CO formation process involved the direct oxidation of hydrocarbon fuels to CO and CO_2. CO was mainly oxidized to CO_2 (Figure 5), as the oxidation of CO under different water injection conditions was essentially the same, with the highest mass value of CO in the cylinder leading to its final formation. The main source of CO in the cylinder is the formaldehyde (CH_2O) decomposition reaction at high temperatures. CH_2O and OH interact and form HCO radicals, and the HCO radicals are further converted to CO [33,37]. However, in some works, the reverse trend is visible, i.e., as the amount of injected water increases, CO emissions increase [36], and this phenomenon is explained by the fact that a two-step mechanism ($CO + OH = CO_2 + H$ and $CO_2 + O = CO + O_2$) is usually used to describe CO formation. During the combustion of natural gas in the engine, H is absorbed from methane and methyl (CH_3) is formed. Subsequently, the methyl undergoes a more complex series of reactions that form CO and ultimately oxidize to CO_2, but these reactions are partially suppressed or slowed down by the addition of water. Therefore, as the amount of water injection increases, the CO concentration increases. However, this source described studies which used lean combustible mixtures.

The results of the carbon dioxide measurements (Figure 5b) show that it practically does not change, or increases very minimally (up to 2%), when proportionally increasing the amount of injected water. This minimal increase can be attributed to the decrease in CO emissions. The fuel burns better, resulting in more CO_2 particles, the products of normal combustion. Carbon dioxide is not poisonous to humans, but this compound directly contributes to global warming. However, this increase is very small and not significant.

The variation of hydrocarbon emissions is presented in Figure 6a. From the results of the experimental study, how it changed with the use of different natural gas mixtures with the additional application of water injection can be seen. The obtained results show that the amount of hydrocarbons increased from 0 to 10% with an increase in the amount of water injected. Water reduces combustion velocity, which leads to incomplete combustion [38], but increasing H_2 fraction in fuel reduces this effect of water, as H_2 has high laminar flame speed and for a mixture with 10% or 15% H_2, HC emissions cha less than 6%. However, in the case under consideration, this part is very small and does not even reach 90 ppm in any of the cases. Such hydrocarbon emission levels are not reached by any spark ignition engine powered by conventional fuels (typically starting at 120 ppm) [30]. Therefore, it can be said that such hydrocarbon emissions are low.



(**a**)



(**b**)

Figure 6. Effect of water injection on HC and NO_x when the engine runs on different fuel mixtures: (**a**) HC dependences; (**b**) NO_x dependences.

The analysis of the research results (Figure 6b) shows that by increasing the amount of injected water from 0 to 120 mL/min, the emission of nitrogen oxides decreases by 67–74% in all cases when gas fuel was used. This happens because the injected water lowers the in-cylinder temperature for compression and combustion, so nitrogen oxides are formed less intensively during the combustion process [39]. Although the additional hydrogen in the gaseous fuel promotes the formation of nitrogen oxides, the injection of additional water is much more significant in reducing the formation of nitrogen oxides. This phenomenon confirms the results described in the literature [29]. It was also determined by the tests that the emission of nitrogen oxides is most effectively reduced in the engine using all tested mixtures of compressed natural gas, with an additional water flow of 120 mL/min.

3.2. Numerical Assessment

The effect of additional water injection on engine in-cylinder pressure and temperature is shown in Figure 7. While the engine was running on CNG, the maximum in-cylinder pressure was 7.38 MPa, and additional water injection of 60 mL/min and 120 mL/min reduced it by 5.8% and 10.5%, respectively. Maximum in-cylinder temperature was reduced by 4.6% and 6.8%, respectively, from 2468 K when the engine was running on CNG. Evaporating water absorbs part of the heat from combustion process and in the after-burn stage of combustion, the in-cylinder temperature decreases on average by about 99 K at 60 mL/min WI and 116 K at 120 mL/min WI. Adding 5% of hydrogen to CNG slightly increases the maximum in-cylinder pressure and temperature to 7.60 MPa and 2484 K, but additional water injection at 60 mL/min decreases these parameters by 4.2% and 4.3%, and at 120 mL/min, by 8.6% and 7.0%. Compared to CNG in-cylinder parameters, water injection has less influence when H_2 is added to CNG. Increasing the H_2 content in CNG up to 10% increases the maximum in-cylinder pressure up to 7.7 MPa, 60 mL/min water injection reduces it by 4.2% as 120 mL/min by 8.6%. Accordingly, in-cylinder temperature decreases from 2498 K by 3.6% and 6.4% as in the after-burn stage of combustion, in-cylinder temperature decreases on average by about 74.5 K at 60 mL/min WI and 87.5 K at 120 mL/min WI. At the highest H_2 fraction of 15%, the maximum in-cylinder pressure was measured at 7.78 MPa and water injection at 60 mL/min decreased it by 4.6%, and at 120 mL/min, by 8.4%. Maximum in-cylinder temperature increases up to 2507 K and WI reduces it by 4.8% at 60 mL/min and 6.8% at 120 mL/min. Increasing the amount of water injected reduces the in-cylinder pressure and temperature because water reduces the laminar flame speed and the rate of heat release, as it also absorbs heat from the combustion. The maximum reduction in-cylinder pressure occurred when the engine was running on natural gas, as CNG has the lowest LHV and flame speed compared to CNG and H_2 mixtures.

Hydrogen additives could increase NO_x emissions and engine knock as it has high LHV and flame speed, as well as a low methane number. However, its use with an additional water injection system reduces in-cylinder pressure, temperature, and the possibility of engine knock. As shown in Figure 8, adding H_2 to CNG combustion will increase the maximum in-cylinder pressure by 3.0%, 4.7%, and 5.5%, respectively, while increasing the H_2 fraction from 5% to 15%. At the same time, the maximum in-cylinder temperature increases by 0.6%, 1.2%, and 1.5%, respectively. As hydrogen has higher LHV, it adds more energy to combustion as well as increasing combustion speed. Additional H_2O injection reduces H_2 influence and prevents engine knock. At 60 mL/min WI and 10% H_2 fraction, the maximum in-cylinder pressure increases just by 0.3% in compared to CNG combustion. If the WI rate was 120 mL/min, even at 15% H_2, the maximum in-cylinder pressure drops to 7.13 MPa and is 3.3% lower than with CNG.

Looking at the results in Figure 8d, which are graphs of all cases studied with all mixtures and all amounts of injected water, it is clear that water has the greatest influence on both pressure and temperature; the more it reaches the cylinders, the more the pressure and temperature decrease. Hydrogen has the opposite effect; the greater its amount, the more the pressure and temperature rise, as it also shortens combustion duration and increases laminar combustion speed. Such a phenomenon is sufficiently well-studied, and the results presented in the work are very similar [40–42].

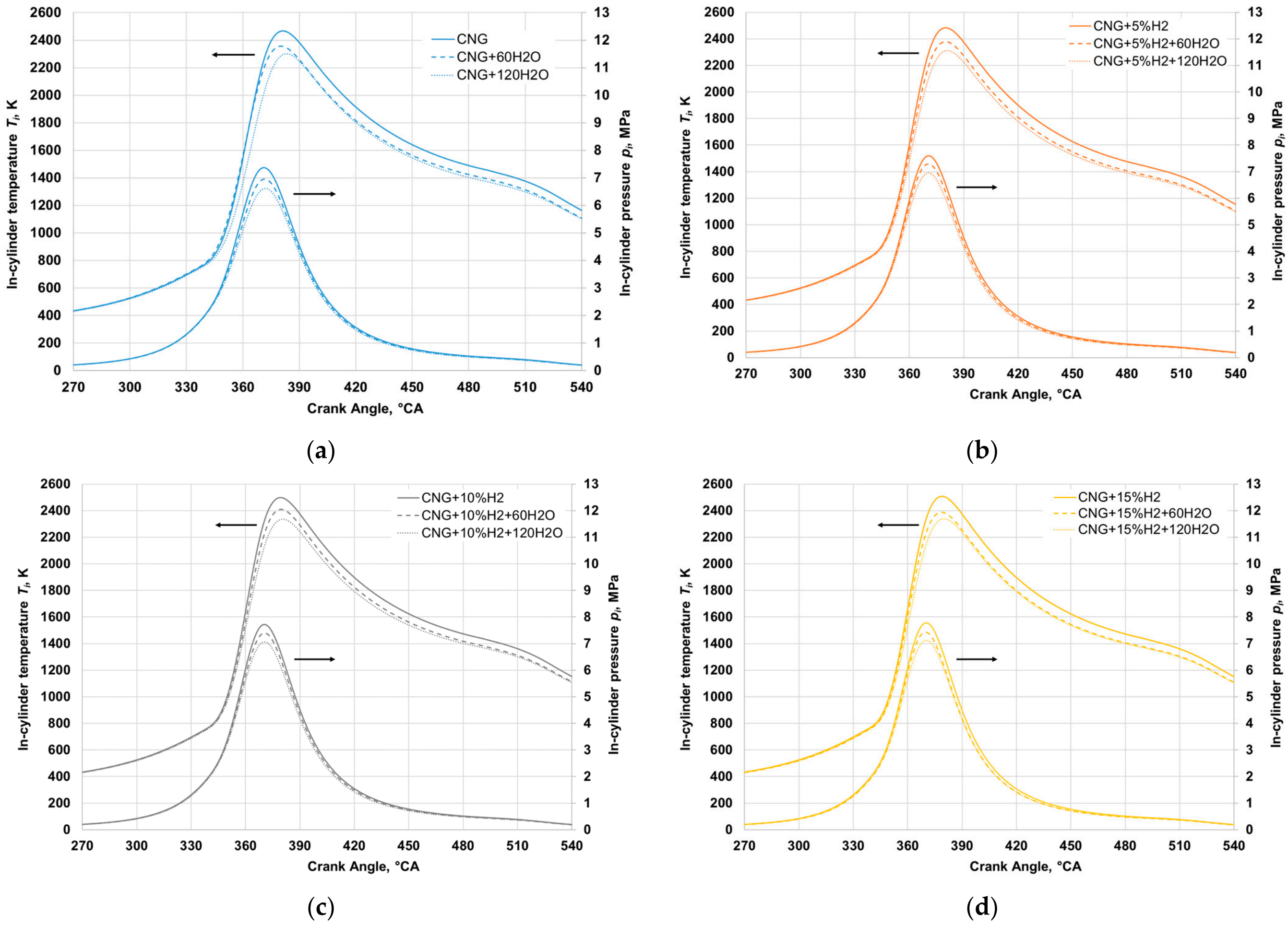


Figure 7. Effect of water injection on in-cylinder temperature and in-cylinder pressure when the engine is running on different fuel mixtures and different amounts of water: (**a**) the engine running on pure CNG, (**b**) the engine running on CNG + 5%H_2 mixture, (**c**) the engine running on CNG + 10%H_2 mixture, (**d**) the engine running on CNG + 15%H_2 mixture.

The simulation results obtained show how the maximum pressure and temperature in the cylinder depend on the amount of water injected using different gas mixtures (Figure 9). It can be observed that the maximum pressure increases by about 1–2% as the amount of hydrogen in the mixture increases. This is due to the same reasons that increase the effective power and reduce the comparative fuel consumption, i.e., the relevant physical and chemical properties of hydrogen (low calorific value, flame propagation speed, etc.). On the other hand, as the amount of water injected increases, the maximum power decreases by about 2–3%. This is explained by the effect of the water on the temperature of the combustion process [40]. As the combustion temperature decreases (and without changing the volume of the combustion chamber), the maximum pressure in the cylinder must directly decrease and, at the same time, power output.

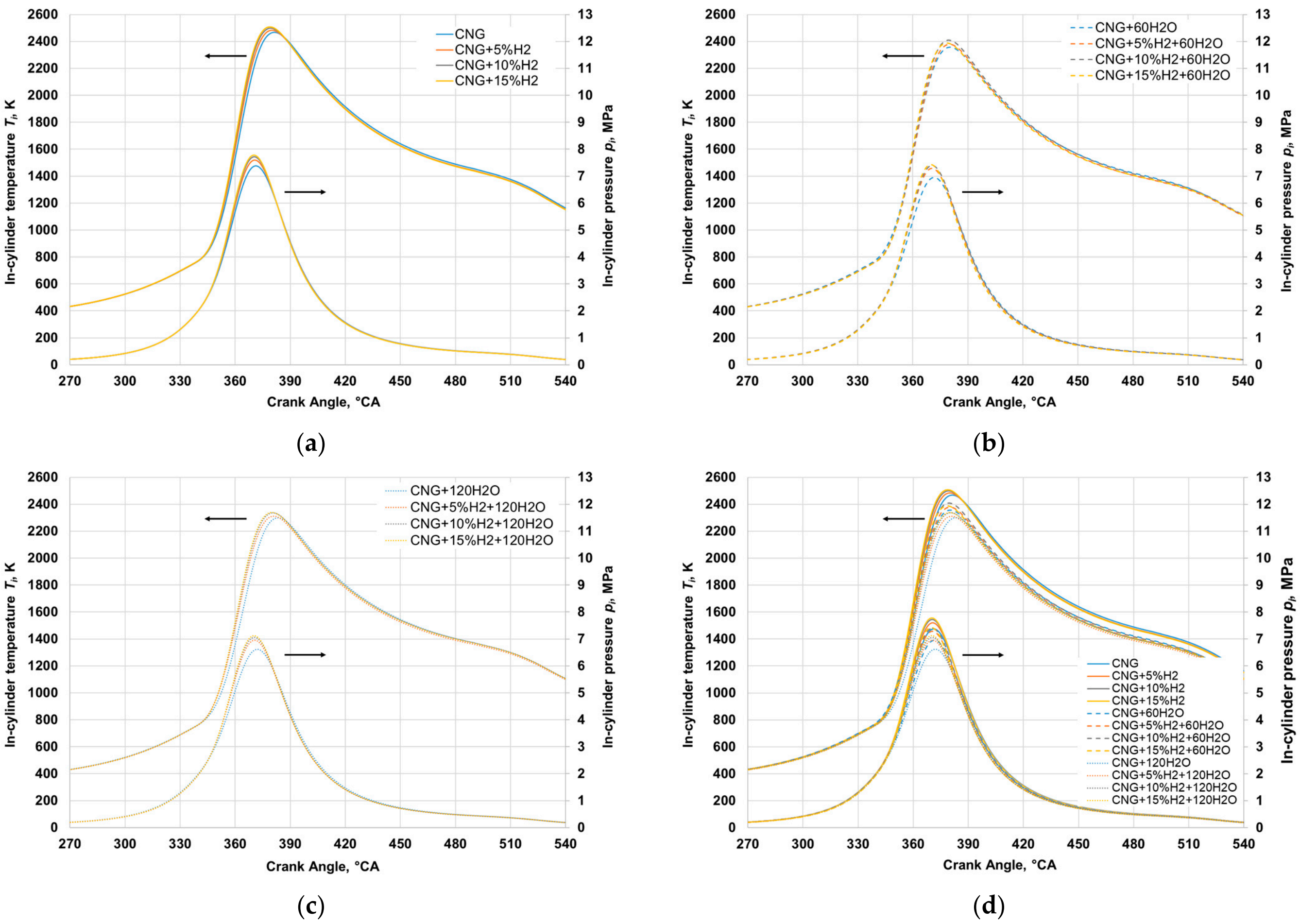


Figure 8. Effect of hydrogen additive and water on in-cylinder temperature and in-cylinder pressure when the engine is running on different fuel mixtures: (**a**) the engine running without WI; (**b**) the engine running with 60 mL/min WI; (**c**) the engine running with 120 mL/min WI; (**d**) all test modes.

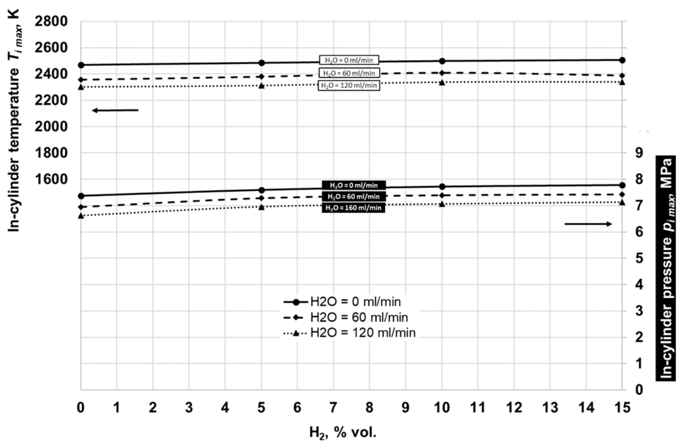


Figure 9. Effect of hydrogen additive on in-cylinder temperature and in-cylinder pressure when the engine is running on different fuel mixtures and different amounts of water.

4. Conclusions

Experimental comparative studies of an SI engine operating on natural gas–hydrogen mixtures, with additional injected water and simulation of in-cylinder temperature and in-cylinder pressure, led to the following conclusions:

1. The addition of 5–15% hydrogen to natural gas has a minimal effect on the fuel consumption of the engine and on many environmental parameters (CO, CO_2, HC), but it has a significant effect on NO_x emissions, which increased by around 20%;
2. The injection of water into the engine combustion system from 0 to 120 mL/min has the most positive effect on CO and NO_x emissions. CO emissions are reduced by an average of 25% in all cases of natural gas and natural gas–hydrogen mixtures used, and NO_x emissions are reduced by 67–74% and are significantly lower than emissions when natural gas is used without the addition of hydrogen;
3. Adding H_2 to CNG combustion will increase the maximum in-cylinder pressure by 3.0%, 4.7%, and 5.5%, respectively, while increasing the H_2 fraction from 5% to 15%, at the same time increasing the maximum in-cylinder temperature increase by 0.6%, 1.2%, and 1.5%, respectively.
4. Evaporating water absorbs part of the heat from combustion process and in the after-burn stage of combustion, the in-cylinder temperature decreases on average by about 99 K at 60 mL/min WI and 116 K at 120 mL/min WI.
5. The addition of hydrogen raises the in-cylinder temperature and pressure, which increases NO_x emissions, but the injected water lowers the in-cylinder temperature, which also helps to reduce NO_x emissions. For an engine running on a 20% hydrogen–natural gas mixture with a 35 kW traction load, to achieve the same level of NO_x emissions as running on pure natural gas, it would be sufficient to inject about 30 mL/min of water into the engine's intake air.

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Abbreviations

bTDC	before top dead center
CI	compressed ignition
CNG	compressed natural gas
EGR	exhaust gas recirculation
GHG	greenhouse gases
HCNG	hydrogen–compressed natural gas mixture
ICE	internal combustion engine
IMEP	indicated mean effective pressure
NG	natural gas
SI	spark ignition
SOC	start of injection
WI	water injection

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