Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(10), 106–122
https://doi.org/10.12913/22998624/208014
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.06.13
Accepted: 2025.08.15
Published: 2025.09.01

Hydrogen with compressed natural gas in 1-cylinder diesel engine: Emission analysis

Maciej Bajerlein[1], Wojciech Karpiuk[1*], Beata Kurc[2], Dmytro Levchenko[3], Rafał Smolec[1], Marek Waligórski[1]

[1] Institute of Powertrains and Aviations, Faculty of Civil Engineering and Transport, Poznan University of Technology, Piotrowo 3, PL-60965 Poznan, Poland
[2] Institute of Chemistry and Electrochemistry, Faculty of Chemical Technology, Poznan University of Technology, Berdychowo 4, PL-60965 Poznan, Poland
[3] Institute of Marketing and Sustainable Development, Lodz University of Technology, Żeromskiego 116, PL-90-924 Łódź, Poland
* Corresponding author's e-mail: wojciech.karpiuk@put.poznan.pl

ABSTRACT

HCNG is a fuel, which as a mixture of hydrogen (H_2) and compressed natural gas (CNG), combines the advantages of both gases. The addition of hydrogen shortens the combustion time, increases the flammability range and enables greater exhaust gas recirculation (EGR) while maintaining cyclic stability and low NO_x emissions. Typical ratios are 10–30% hydrogen and 70-90% methane, although the composition depends on the application. Hydrogen acts as a catalyst, improving the properties of the mixture. The Wobbe index allows to assess the impact of the gas composition on the engine behavior. HCNG combines the safety advantage of slow-burning CNG with the efficiency and burning rate of hydrogen, offering better combustion and emissions than each gas separately. The challenge in the use of HCNG is the need to introduce small modifications in the internal combustion engine due to the differences in self-ignition temperatures. The self-ignition of CNG and hydrogen requires a higher temperature than diesel (approx. 500 K), which forces the initiation of combustion by diesel injection. As a result, HCNG can be used in most classic diesel engines. This fuel has a higher energy volumetric storage density than pure hydrogen, which reduces the need to transport large amounts of fuel. Disadvantages include the lack of appropriate infrastructure, fuel and vehicle standards and the need for additional safeguards. The aim of the study was to check the emission levels of a single-cylinder diesel engine powered by HCNG compared to conventional fuel. It has been shown that the use of HCNG effectively reduces CO emissions due to the lack of carbon in hydrogen and its high combustion rate, which intensifies the process and improves its efficiency. The higher hydrogen content further stabilizes methane combustion and increases the homogeneity of the mixture. HCNG also reduces hydrocarbon (HC) emissions, compensating for the ignition delay and slow speed of the CNG flame. At higher engine loads, these effects are more visible, leading to more efficient combustion. Particulate matter (PM) emissions are reduced due to the homogeneous mixture resulting from the high diffusivity of hydrogen. PM reduction is more visible at lower loads. Higher combustion temperatures in HCNG promote the formation of NO_x, which results from the intensification of combustion by hydrogen and excess oxygen, according to the Zeldovich mechanism. By analyzing emissions, the authors showed the great potential of using HCNG in a diesel engine. At the same time, the main challenges that should be faced in order to popularize this solution were indicated.

Keywords: hydrogen, CNG, HCNG, diesel engine.

INTRODUCTION

Fast-paced global industrialization and equally fast-growing automotive industry mean that the demand for fossil fuels is constantly growing. According to the IEA report [1], global energy demand will double by 2050 compared to the situation at the beginning of the 21st century. On the one hand, the use of renewable energy sources will increase very strongly until then, but on the other hand, the use of fossil fuels (oil, natural gas, coal) will continue to be at a high level [2, 3]. This is therefore a global problem, as these types of fuels are non-renewable fuels, resulting in a negative impact on the environment. Referring this problem directly to internal combustion engines, which boost the main branches of industry i.e. automotive and transport industry, it is necessary to look at the use of diesel for the above-mentioned purposes. Undoubtedly, diesel is the most commonly used petroleum-based fuel, and its consumption is constantly growing worldwide [4]. The popularity of compression ignition engines over gasoline engines can be explained by the fact that they have higher thermal efficiency, better reliability and durability. They are also engines that consume less fuel, with reduced emissions of carbon dioxide and unburned hydrocarbons [5, 6]. However, diesel engines have some significant disadvantages – they emit toxic nitrogen oxides (NO_x) [7] and very harmful particulate matter (PM)/soot, which is mainly due to burning heterogeneous mixtures [8,9]. Although carbon dioxide emissions from compression ignition engines are lower than those from ignition engines, they do occur. This is important due to the fact that CO_2 is one of the greenhouse gases, so it is included in the emission regulation standards. In 2020, the European Union set the average CO_2 emissions of new vehicles (cars) at a maximum of 95 g/km, with this level to be reduced by 55% by 2030. By 2024, the average emission level for new vans is 147 g CO_2/km according to the older NEDC standard, while from 2030 to 2034 an emission reduction of 50% is required to the level of 90.6 g CO_2/km [10, 11]. The American EPA for passenger car models produced in 2023-2026 sets itself the goal of a gradual reduction of emissions – in 2026 the maximum allowed emission is to be about 161 g of CO_2 per mile (approx. 100 g CO_2/km). In order to meet the emission requirements, vehicle manufacturers were forced to use solutions such as, for example, particulate matter filters or selective catalytic reduction systems. These systems effectively reduce the emission levels of particulate matter and nitrogen oxides. The use of precious metals in the construction of this type of systems makes these solutions expensive.

Therefore, it is necessary to look for alternative solutions allowing, as a result, to meet increasingly stringent emission standards. A revolutionary solution was supposed to be a widespread transition to electric vehicles powered by batteries and fuel cells [12, 13]. It was to be a direct alternative to classic solutions. The popularity of this solution is growing, but in the short term these vehicles will not be able to compete with vehicles equipped with internal combustion engines [14, 15]. This is due to problems related primarily to the range and load capacity of these vehicles. The problem is also the infrastructure, which is still developing and at a different pace depending on the country. Electric vehicles are still a more expensive option, despite the fact that many countries introduce subsidies for their purchase. In addition to the above-mentioned problems, the emission aspect related to electric vehicles should also be taken into account. Transport policy is often based on the erroneous assumption that battery electric vehicles are "zero-emission" vehicles. The analysis of their life cycle indicates that they do not lead to a significant reduction in CO_2 emissions, taking into account the energy that is necessary for the production of batteries and the use of vehicles [16]. In addition, the impact of extraction of materials needed for the production of batteries on health and the environment is very significant – the extraction of lithium and cobalt, i.e. the key raw materials used for the production of lithium-ion batteries, requires a large amount of water and energy. There are also humanitarian problems, concerning, for example, the acquisition of the above-mentioned raw materials by children, which is a sad everyday reality, for example, in the Democratic Republic of the Congo. Problems with the use of electric vehicles are therefore of a different nature. Taking its applicability into account, it should be remembered that in order to replace light commercial vehicles with electric vehicles, the available battery capacity must increase more than a hundredfold compared to 2021 [17], which seems unattainable at the moment.

Another approach to solving modern transport problems is the use of alternative fuels. This is a very broad issue, because it can apply to both CI and SI engines, it can be an approach in which a completely new fuel is sought, but also one in which conventional fuel is co-fired with alternative fuel. Limiting this issue to compression ignition engines, which are discussed in this article, one of the gaseous fuels that has been recognized as a substitute for classic fuel is CNG, i.e. compressed natural gas. The main component of CNG is methane (CH), which has a simple structure and a high hydrogen to carbon ratio, which promotes lower carbon dioxide (CO_2) emissions during combustion compared to diesel.

Moreover, CNG does not mix or dilute the lubricating oil and does not cause deposits in the combustion chamber, which consequently extends the service life of the piston rings [18]. CNG is introduced into the engine as a dual-fuel, which requires modification of the intake system and diesel injection. Modern systems can use adaptive technologies to optimize operating parameters. CNG has a high octane number (110–120), which makes it resistant to self-ignition, requiring the initiation of combustion by a small dose of diesel. The high octane number of methane is an additional advantage, allowing – by increasing the compression ratio – to increase the thermal efficiency or strengthen the ability to supercharge the engine [19]. The calorific value of CNG is about 50 MJ/kg, which makes it competitive with diesel (43 MJ/kg). However, due to the lower energy density (by volume), it requires more space for fuel tanks, which limits its use in small cars, but is very beneficial for large vehicles such as city buses. The combustion process depends on the proportions of CNG and diesel and on operating parameters such as injection pressure and ignition timing. According to research conducted by S. Bari and S.N. Hossain [20], with diesel consumption of 20% or less, engine knock combustion occurred. Therefore, the engine should always run with diesel consumption above 20%. Notwithstanding the above statement, CNG combustion generally emits less particulate matter (PM) and less soot than diesel, which reduces problems related to DPF pollution and the emission of carcinogens [21, 22]. This is due to the fact that diesel oil contains aromatic compounds that at high temperatures cause the polymerization of carbon and, consequently, the formation of soot – there are no such compounds in CNG, which reduces PM emissions. Compressed natural gas, apart from its undoubted advantages, also has some disadvantages. The use of compressed gas can lead to increased emissions of carbon monoxide (CO) and unburnt hydrocarbons (UHC). The thermal efficiency of the motor can be reduced using CNG. This fuel may also cause locally lean mixtures in the combustion chamber, the formation of which results in the failure to sustain flame propagation. This results in the formation of flame extinction areas, increasing the aforementioned CO and UHC emissions. The slow burning rate resulting from low flame propagation velocities is also a problem. CNG has a poor ability to burn a lean mixture, which results in incomplete combustion, a high underburning coefficient and large cyclic fluctuations when burning a lean mixture [23].

Another promising alternative fuel/energy carrier for transport is hydrogen. It is one of the most widespread chemical elements in the world. Unfortunately, it is most often found in combination with other elements, which does not facilitate its quick and cheap acquisition. The challenge is therefore the production of pure hydrogen. The demand for hydrogen is most often met on a global scale by the use of fossil fuels. There are several leading methods – hydrogen is mainly produced in the world in the following processes:

- reforming natural gas (methane), about 47%;
- by gasification of coal or coke, about 27%;
- by partial oxidation of heavy hydrocarbons from petroleum (mainly in refineries), about 22%;
- using an electrolysis process, mainly for the production of chlorine from sodium chloride, about 4% [24].

In relation to classic internal combustion engines, this fuel is most often considered as an alternative that can be used in gasoline engines. However, it can also be used in compression ignition engines. Compared to conventional fuels, the advantage of hydrogen is the lack of carbon. It is highly flammable, odorless and burns with a colorless flame. Hydrogen has almost three times the calorific value (120 MJ/kg) of diesel. Due to the low density, a large amount of H2 is required to produce the same amount of energy as these fuels, which can lead to storage problems. Therefore, taking into account the energy density per unit volume, conventional fuel has a higher calorific value. The most popular method of hydrogen storage is compression in high-pressure tanks [25]. The advantage of hydrogen is also that it has high flammability limits, so it can work on lean mixtures [26]. The speed of the hydrogen flame is much higher than the speed of the diesel flame. For hydrogen under stoichiometric conditions, this speed is about 2.7 m/s, which is about 10 times higher than for traditional hydrocarbon fuels such as gasoline or diesel. Although a higher flame speed may result in faster and fuller combustion of the fuel, it does not necessarily translate into higher thermal efficiency as it may result in the loss of some of the heat generated during the combustion process before it is converted into useful work. Therefore, it should be assumed that a higher flame speed does not always mean a higher thermal efficiency in a hydrogen-powered diesel engine. Another problem should also be kept in mind – hydrogen-powered diesel engines emit more NO_x due to higher temperatures in the cylinder [27]. Knock combustion resulting from a sharp increase in cylinder pressure when the air-fuel mixture ignites unevenly may also be a problem. This is because hydrogen can ignite before the piston reaches the upper dead center (GMP). This is also facilitated by local zones with different fuel concentrations. Due to the low hydrogen activation energy, different parts of the mixture may ignite simultaneously. However, this is due to many factors such as the swirl of the load or the shape of the combustion chamber. Hydrogen as a gas is characterized by high diffusivity, which allows for greater homogeneity of the fuel mixture. This, in addition to the situation described above, translates into better, i.e. more homogeneous mixing with air, which generally improves the combustion condition. However, the high self-ignition temperature of $_{H2}$ (depending on the pressure – over 800 K) means that this fuel in a classic internal combustion engine cannot work as the only fuel. Therefore, this gas must always cooperate with another fuel with a lower auto-ignition temperature to act as a source of ignition.

As it has been shown, both CNG and H2 have their advantages and disadvantages. Many researchers have noticed this rule, which resulted in the concept of burning both gases as HCNG. This is due to the unique characteristics of hydrogen, which allows it to be used together with natural gas. Adding hydrogen to natural gas may shorten combustion time and increase flammability range. In addition, the introduction of hydrogen allows to extend the scope of exhaust gas recirculation (EGR), while maintaining cyclic stability and low emissions of NO_x [28]. The behaviour in the engine of a mixture of hydrogen and compressed natural gas depends largely on the proportions of both gases. A special patented and proven case is a mixture called Hythane, in which the percentage of both components is specified in detail. A typical proportion is about 10–30% hydrogen and 70–90% methane, although the exact composition may vary depending on the application and technology. Hydrogen acts as a catalyst, improving the properties of the mixture. The influence of the gas composition on the engine behavior can be characterized using the Wobbe index. If the Wobbe index remains constant, a change in the gas composition will not lead to a noticeable change in the air-fuel ratio and combustion rate. HCNG combines the advantages of a safe, slow-burning fuel like CNG with an efficient, fast-burning fuel like hydrogen. Comparison of the properties of hydrogen, CNG and the mixture of both gases, i.e. HCNG is shown in Table 1.

The challenge facing the use of HCNG is to make minor modifications to the internal combustion engine. This is due to the differences in self-ignition temperatures, which for diesel is about 500 K. This temperature is achieved by increasing the air temperature and its compression during the compression stroke. The self-ignition temperature of CNG and hydrogen is higher and cannot be achieved without appropriate engine modifications. The same is true for HCNG. Here, it was assumed that it was necessary to initiate combustion with diesel fuel, which acts as a source of ignition of the HCNG mixture. The advantage of this approach, however, is the possibility of using HCNG in almost every classic diesel engine. HCNG has a higher energy storage density compared to pure hydrogen, which allows less fuel to be transported in the vehicle. The disadvantage of the concept of using HCNG is the lack of appropriate infrastructure and standards for both fuel and vehicles using it. The use of gases also necessitates the use of safety devices.

Table 1. Properties of hydrogen, CNG and HCNG [29]

Properties	Hydrogen	CNG	HCNG
Flame speed (m/s)	236	42	120
Calorific value (MJ/kg)	142	55	92
Stoichiometric A/F ratio	34:1	17:1	23:1
Flammability limits (Vol%)	4-75	5-15	5-35.
Minimum ignition energy (mJ)	0.02	0.28	0.21
Auto ignition temperature (K)	858	813	825

HCNG research was conducted at the Lords Institute of Engineering and Technology in India. The authors of the article [18] introduced 10 and 20% mass shares of HCNG into the combustion chamber in the HCNG-diesel dual fuel mode. The experiments were carried out at three different injection opening pressures, i.e. 200, 220 and 240 bar, at full load and calculated performance characteristics. The effect of the injection working pressure (IOP) on emissions was measured and compared to the pure diesel mode. Injection pressure variability was evaluated to optimize performance and emission characteristics. Brake thermal efficiency (BTE) increased by 1.2% at 220 bar. Minimum BSFCs of 0.2302 kg/kWh, 0.2114 kg/kWh were recorded for 220 bar with a varying 20% HCNG ratio. It was noted that CO and UHC decreased as the injection pressure and HCNG content of the mixture changed. This was due to the lack of carbon in hydrogen and better atomization of fuel droplets. NO_x emissions increased from 200 to 220 bar of injection pressure, and maximum NO_x values were observed at 220 bar with 20% HCNG with a 25% increase compared to pure diesel.

Similar results were obtained by Subramanian [30], who carried out tests on a 6-cylinder high-power engine, optimized for operation on an 18% HCNG additive. The initial HCNG engine performance was compared to CNG, and then the engine was subjected to a 100-hour HCNG endurance test. The results of the tests showed that HCNG resulted in a reduction of CO, THC and CH4 emissions by 39%, 25% and 25%, respectively, while NO_x emissions increased by 32% compared to CNG. The average engine power remained at a similar level with HCNG at the end of the endurance test. After the endurance test, CO emissions increased, while THC, CH_4, NO_x and CO_2 emissions decreased even more, remaining below Euro-IV standards. The author also proved that the conversion efficiency of the catalytic converter was 95-97% at the end of the stress test.

The authors of the article [31] also conducted tests on the 6-cylinder engine. This engine used the concept of lean combustion. The choice of the engine was based on its popularity in urban transport. The study evaluated the concept of lean combustion for various HCNG mixtures, as well as CFD simulation of the combustion process. The aim of the study was to determine the optimal mixture. The results showed that CNG powered engines are characterized by slow combustion speed and poor lean combustion capability, which requires engine operation at a stoichiometric ratio, with relatively low thermal efficiency. The lean combustion capacity and the combustion speed of the gas engine flame have been improved by the addition of hydrogen i.e./ fuel with a higher combustion speed. The lean combustion HCNG engine has demonstrated a significant improvement in efficiency, reducing fuel consumption and hydrocarbon emissions. When the share of hydrogen to coal in the HCNG fuel increased, it resulted in reducing emissions of carbon compounds such as CO, CO_2 and HC.

Zhou et al. [32] conducted experimental studies on combustion and emissions of a diesel engine using diesel as a pilot fuel and methane, hydrogen and a mixture of methane and hydrogen (HCNG) as gaseous fuels at 1800 rpm-1. The effect of HCNG on the maximum values of mean useful pressure (BMEP) and heat generation was small at low and medium loads. At high load, high combustion temperature and a large amount of pilot fuel contributed to better combustion efficiency for all types of gaseous fuels and increased the peak pressure in the cylinder. Hydrogen enrichment of methane gradually increases the maximum pressure values in the cylinder. The addition of hydrogen to methane contributed to a proportional reduction in CO/ CO_2 /HC emissions without adversely affecting NO_x emissions. The authors proved that in the case of particulate matter emissions, methane and hydrogen could suppress the emission of particulate matter. It was observed that the 30% share of hydrogen in methane best red6ces the emission of particulate matter.

Vadlamudi et al. [33] also studied the emission of an engine using HCNG. The engine intake manifold supplies hydrogen/CNG and hydrogen mixtures. In the case of dual and single fuel operation with diesel fuel, dual fuel operation produced higher cylinder pressure (73.39 bar) and showed better combustion. Due to the use of HCNG, high variability in ignition delay and combustion duration compared to pure diesel has been observed. Fuel enrichment with hydrogen reduced fuel consumption. In dual fuel mode, a significant reduction in engine pollutants compared to diesel oil is observed. Hydrogen substitutes reduce THC and CO_2 emissions by 30-35% and 3–4%, respectively. Working on dual fuel emitted less smoke (5–10%) than working on clean diesel. The authors proved that regardless of the injection pressure, emissions such as NO_x, CO_2 and smoke are better for all dual-fuel engines than for conventional CI engines.

The authors of this paper, seeing the potential of using HCNG, decided to carry out tests using a compression ignition engine, which were aimed at verifying the emission levels of basic harmful compounds. Unlike previous studies on HCNG, this research utilizes a single-cylinder engine with intake-port fuel admission, and examines a wider range of hydrogen fractions (up to 60% H_2 by volume) to assess extreme cases. This approach provides new data on emissions behavior under these conditions.

MATERIALS AND METHODS

In order to verify the HCNG emission levels, it was first of all necessary to choose the method of supplying gaseous fuel to the tested engine. There are several basic methods in this regard. They have been described in an interesting way by Rueda-Vázquez et al. [25]. The authors emphasized that the advantage of using hydrogen is the possibility of using the same injection methods as in the case of CNG and LNG. These methods include the use of:
- carburetor,
- inlet manifold injection,
- inlet port injection,
- direct injection.

The authors presented these methods in the diagram shown in Figure 1.

The simplest method is to use a carburetor - the fuel is mixed with the air by the carburetor before entering the intake duct. This method does not require a high fuel supply pressure, which is an advantage, but the presence of an air and H2 mixture in the intake manifold is associated with some danger. If the intake valve opens, the flame may spread through the intake manifold, causing backfire resulting in engine damage [26]. Subsequent methods use hydrogen injection. When injected into the intake duct, the fuel supply pressure will be higher compared to the carburetor injection, because there is no increase in the velocity of the intake air and, consequently, the air pressure is not reduced. The injection point is located in this solution near the intake valve (approx. 10–15 mm). In the case of injection into the collector, the distance is much greater, usually between 100 and 200 mm [34]. However, it should be remembered that the number of injectors in the indirect injection method should correspond to the number of cylinders. This ensures the same amount of injected gas for each cylinder. In the direct injection method, hydrogen/CNG/HCNG directly enters the combustion chamber through direct injection, which can be carried out under high pressure (HPDI) or low pressure (LPDI) [26]. LPDI occurs near the lower dead center (BDC) at the end of the intake phase, while HPDI occurs after the compression phase. The advantage of this method is to minimize back ignition. Therefore, it is a relatively safe method. The disadvantage of the method is the high thermal stress of the injectors.

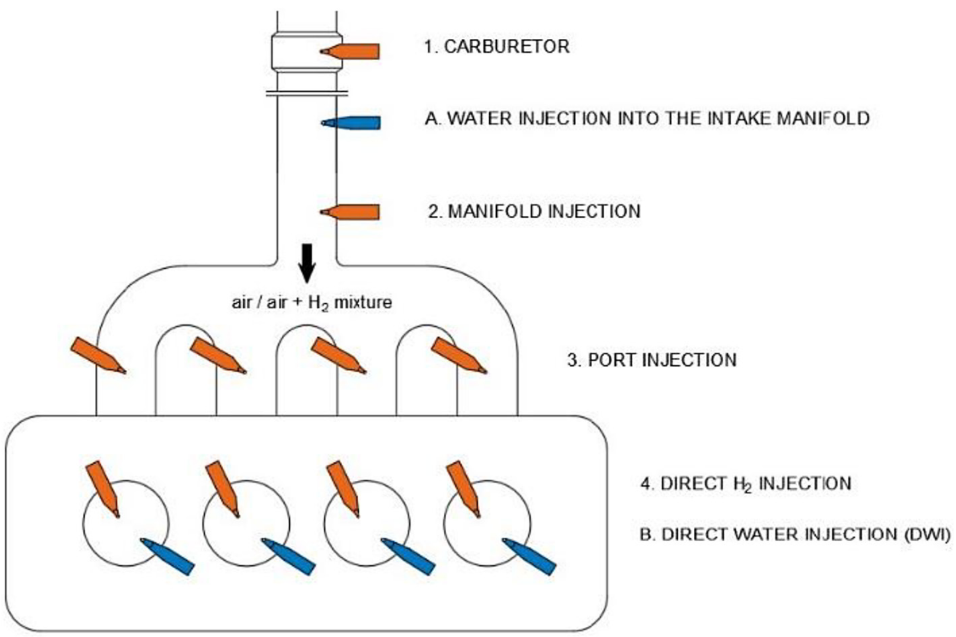

Figure 1. Schematic drawing of the different H2 (orange) and water (blue) injection techniques [25]

The tests of the authors of the paper were carried out on a engine brake stand. Thanks to the use of 1-cylinder SB 3.1 research engine, it was possible to determine the effect of the addition of hydrogen from CNG on the concentrations of toxic exhaust compounds emitted by the drive unit as a result of hydrogen co-firing with diesel fuel using a conventional injector with a 6-hole atomizer. Injection of gases took place into the inlet channel (manifold).The test bench used at this stage consisted of several main parts:

- test engine SB 3.1 with asynchronous generator brake AMK ASYN type DW13-170-4-AOW (Figure 2),
- the 4th generation common rail fuel supply system,
- gaseous fuel supply system - hydrogen,
- electronic control system of the test system.

The basic parameters of the test engine are presented in Table 2. The second part of the station is a laboratory common rail fuel supply system of the 4th generation (Figure 3). The pump, together with the drive system shown below, is a separate part of the station and is driven by an independent electric motor, ensuring smooth regulation of the rotational speed. This type of pump is used in modern power supply systems for compression ignition engines, enabling injection pressures of 200 MPa. The third part of the station is the gaseous fuel supply system, in the case under consideration supplied to the intake manifold using a low-pressure mechanical flowmeter from Bronkhorst. Two flowmeters were used, allowing the flow of hydrogen (Figure 4).

Hydrogen and CNG were stored as compressed gas at pressures of 150 and 200 bar respectively in commercially available cylinders. The cylinders are equipped with indicators for reading the internal pressure and valves for pressure reduction. In order to suppress the pressure fluctuations in the intake duct, which are particularly common in 1-cylinder engines with a large displacement, flame retraction limiters for hydrogen and CNG are used at the inlet. In addition, along with the flame retraction limiter, a flame limiter is also used in the hydrogen supply line.

For the tests, an analyzer was used to measure the harmful components of SEMTECH DS flue gas (Figure 5). The most important parameters of the device are presented in Table 3 and the operating diagram is presented in Figure 6. The flue gas sample is taken by the exhaust gas mass intensity probe and delivered by a heated route that maintains a temperature of ^{191oC}. The exhaust gases are filtered from particulate matter (in the case of CI engines) and the concentration of hydrocarbons in the fid analyzer (Flame Ionization Detector) is measured. Then the sample is cooled to ^{4oC} and the concentration of nitrogen oxides and nitrogen dioxide is measured in the NDUV (Non-Dispersive Ultraviolet) analyzer, and the concentration of carbon monoxide and carbon dioxide is measured in the NDIR (non-dispersive infrared) analyzer. Oxygen is measured with an electrochemical sensor.

RESULTS AND DISCUSSION

The tests consisted in performing engine load characteristics with simultaneous measurement of concentrations of toxic components of exhaust gases. During the preparation of load characteristics for 10, 65 and 95 Nm and rotational speeds of 1100 rpm, the content of basic harmful components in the flue gas, i.e.: CO, HC, NO_x and concentrations of PM, which are presented in the following drawings, was recorded. Measurements of the concentration of SB 3.1 engine toxic compounds were made at selected engine operating points. The parameters that were changed were: the rotational speed of the engine crankshaft and the load, determined by the fuel dose delivered to the engine cylinder. Measuring series for diesel fuel and diesel fuel with the addition of hydrogen from CNG were made for the same engine settings. The load was each time determined by the dose of fuel injected into the engine combustion chamber; which was a variable parameter. The values of the setting parameters were adopted on the basis of the previously described research algorithm. The values of the injection parameters were adopted from the range of engine operation, in order to obtain the greatest possible similarity of the injection system operation to the actual conditions when the engine is powered. The tested hydrogen additive settings for conventional fuel are presented in Table 4.

In the tests, the concentrations of exhaust components were continuously recorded during 60 seconds of engine operation at each point, which were repeated 10 times. The standard deviation for repeated measurements was within 5% of the mean for all reported values, indicating the trends are significant beyond experimental error. The following emission test results performed on the SB 3.1 engine are averaged values. The

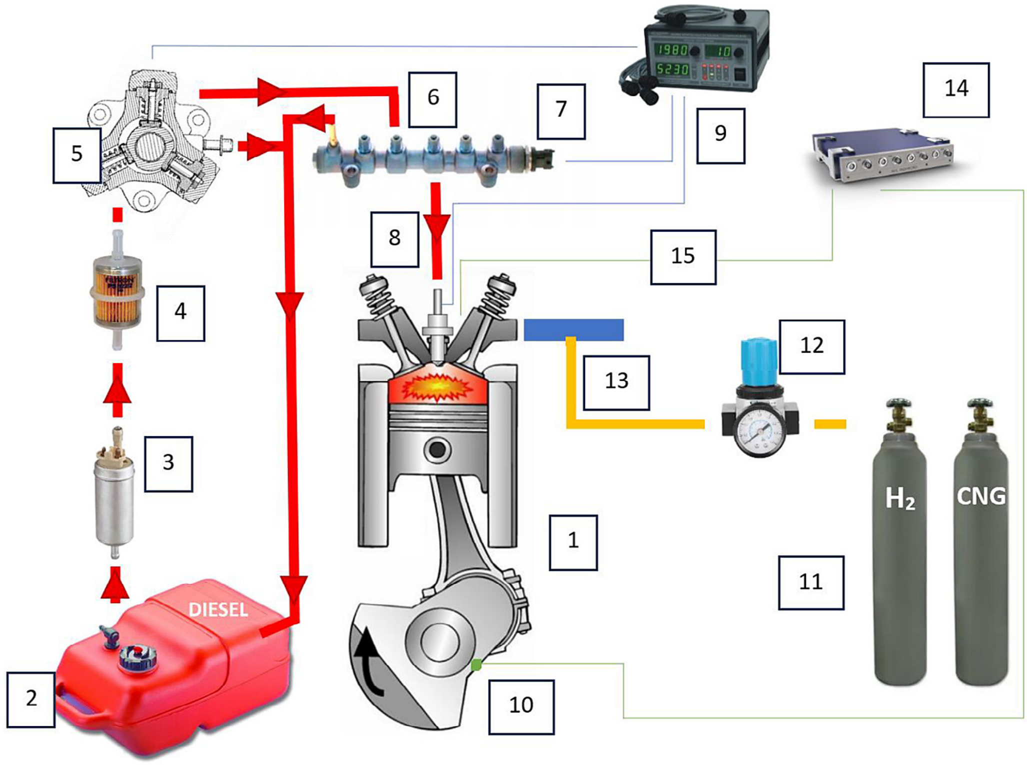

Figure 2. Diagram of the test bench used in engine tests: 1 – SB 3.1 engine, 2 – diesel fuel tank, 3 – Low pressure pump, 4 – Fuel filter, 5 – High pressure pump, 6 – common rail, 7 – Fuel pressure sensor in the rail, 8 – CR injector, 9 – CR controller, 10 – Crankshaft position sensor, 11 – H2 and CNG cylinders, 12 – Reducer with one-way valve, 13 – hydrogen and flammable gas supply system, 14 – computers recording the course of indicator tests, 15 – signal from the indicator pressure sensor

performed experimental investigations on the SB 3.1 engine operating at 1100 rpm confirmed the strong impact of using hydrogen and CNG as co-fuels with diesel in reducing harmful exhaust emissions. The results demonstrate that increasing the hydrogen content in the HCNG blend significantly influences emission characteristics across various engine loads (10, 65, and 95 Nm).

Table 2. Selected parameters of the SB3.1 test engine

Cylinder diameter	127 mm
Piston stroke	146 mm
Engine displacement	1.850 dm³
Torque	110 N·m at 1200 rpm
Compression ratio	15.75
Crank Ratio	0.263
Connecting rod length	277 mm
Intake valve opening angle	4° before GMP
Intake valve closing angle	57° after DMP
Exhaust valve opening angle	42° before DMP
Exhaust valve closing angle	24° after GMP

The relative reduction in CO emissions was the most prominent and consistent across all tested conditions. This effect becomes more noticeable with increasing hydrogen doses, particularly under low and medium load conditions. The DF+H60+CNG configuration reduced CO levels by approximately 25% at 10 Nm and around 15% at higher loads, compared to neat diesel fuel. This reduction is attributed to hydrogen's role in enhancing combustion efficiency, due to its high flame speed, excellent diffusivity, and zero carbon content. These properties improve the uniformity of the air-fuel mixture and enable more complete oxidation of carbon compounds. Figure 7 shows the relative differences in CO under load characteristics for n = 1100 rpm.

The use of hydrogen and CNG in the co-firing of diesel fuel has effectively reduced carbon monoxide (CO) emissions. Hydrogen, which is carbon-free, effectively intensified the combustion process – its addition to CNG raised the combustion temperature, improving the entire process. Effective compensation with hydrogen, a relatively low speed of the compressed natural gas flame,

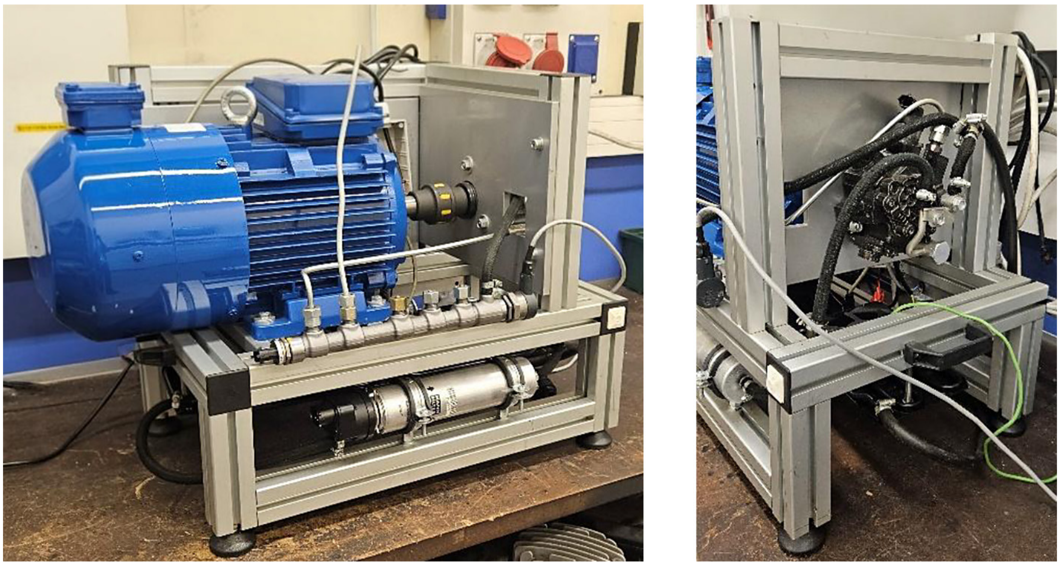

Figure 3. 4th Generation common rail fuel supply system

Figure 4. View of Bronkhorst hydrogen flow meters

Figure 5. SEMTECH DS analyzer and flow meter for measuring exhaust gas mass flow rate

Table 3. Characteristics of the SEMTECH DS mobile fuel gas analyzer

Parameter	Measurement method	Accuracy
The concentration of compounds $COHCNO_x = (NO+NO_2)CO_2\ O_2$	NDIR – non-dispersive (infrared), range 0–10% FID – flame ionization, range 0–10.000 ppm NDUV – non-dispersive (ultraviolet), range 0–3000 ppm NDIR – non-dispersive (infrared), range 0–10% electrochemical, range 0–20%	±3% ±2.5% ±3% ±3% ±1%
Exhaust gas flow	mass flow rate Tmax up to 700oC	±2.5% ±1%
3. Warm-up time	15 min by car	-
4. Response time	T90 < 1 s	-
5. Supported diagnostic systems	SAE J1850 / SAE J1979 (LDV) SAE J1708 / SAE J1587 (HDV) CAN SAE J1939 / J2284 (HDV)	-

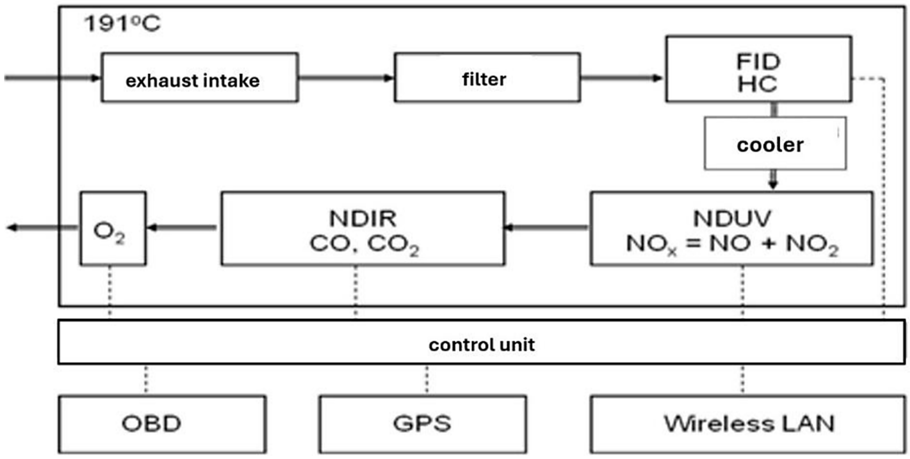

Figure 6. Diagram of the SEMTECH DS instrument with marked fuel gas flow and order of measurement of harmful compounds

Table 4. Setting parameters of SB 3.1 engine fueled by diesel fuel (DF) and hydrogen additive

Item	Designation	Hydrogen dose [l/min]	CNG dose [l/min]
1.	DF	-	-
2.	DF + H5 + CNG	5	10
3.	DF + H20+ CNG	20	10
4.	DF + H60+ CNG	60	10

which usually results in incomplete combustion and increased CO emissions, was also most likely important. Hydrogen is therefore a promoter of this chemical reaction and visibly increases the flammability of methane. This is especially evident when increasing the hydrogen content in HCNG. Another very important feature of hydrogen, which has an impact on reducing CO emissions, is its high diffusivity coefficient. This improves the homogeneity of the air-fuel mixture, contributing to its better combustion. Most likely, according to research conducted by Mansor MRS et al. [35] hydrogen can also accelerate some significant oxidation reactions and improve methane combustion stability by increasing the concentration of OH, H, and O radicals, thereby reducing CO emissions.

Similar positive effects were observed using HCNG in relation to HC emissions (Figure 8). The improved combustion in lean and marginal zones of the chamber, where fuel particles may otherwise remain unburned due to wall and gap effects, was facilitated by the higher reactivity and diffusivity of hydrogen. As a result, the DF+H60+CNG mixture achieved a nearly 20% reduction in HC emissions at low load and approximately 15% at high load.

The positive effect in hydrocarbon emissions using HCNG results again from the fact of replacing coal with hydrogen. A feature of the use of hydrogen in a classic combustion engine is, among other things, an increase in the H/C ratio, which noticeably reduces carbon-based emissions. Also,

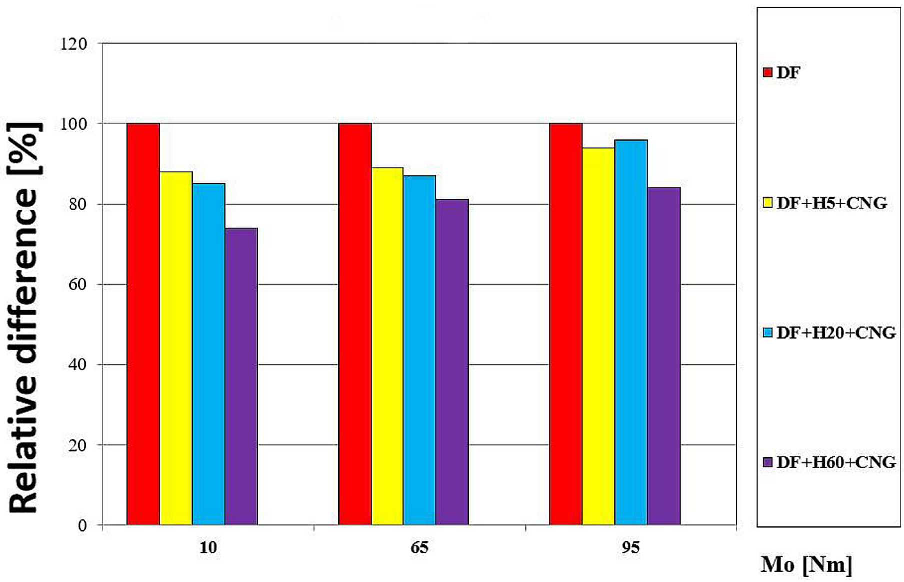

Figure 7. Relative difference of CO in load characteristic conditions for n = 1100 rpm

as in the case of CO, it is important to improve the burning rate of the gaseous fuel. Thus, hydrogen has a positive effect on higher ignition delay, lower flame velocity and lower CNG combustion temperature. Its addition compensates for the above-mentioned effects. According to some researchers, the features of HCNG make this fuel better able to cope with the wall and gap effects. The wall effect in an internal combustion engine refers to the behaviour of the mixture of fuel and air near the walls of the combustion chamber, such as the walls of the cylinder, valves or other internal surfaces of the engine. When the air-fuel mixture flows through the cylinder, due to the proximity of the wall surface (e.g. cylinder), some of the fuel and air molecules do not have enough energy to spread evenly and may settle on the walls. Similarly, in the case of the gap effect - when narrow spaces (gaps) are created between various engine elements, such as valves, piston - cylinder, or between the elements of the inlet and outlet system. Both phenomena have an adverse effect on hydrocarbon emissions. The use of hydrogen, hydrogen and CNG thanks to the higher flame speed allows to effectively reduce the negative impact of the above-mentioned phenomena.

Based on the analysis of the graph, a clear impact of engine load on hydrocarbon emissions can also be observed. Lower engine load levels did not result in a significant reduction in hydrocarbon emissions. This is due to the combustion of lean mixtures. Increasing the ratio of fuel to air under increased load conditions allows for improved stability and combustion efficiency. As a result, combustion is complete, which has a positive effect on HC emissions.

The authors also studied the emission of particulate matter (PM) using different ratios of hydrogen to carbon (Figure 9). PM emissions also decreased significantly, especially at higher loads. For example, PM levels dropped by more than 30% in the DF+H60+CNG case at 95 Nm. This is due to the faster, more homogeneous combustion process enabled by hydrogen, which supports soot-free oxidation. The presence of hydrogen promotes cleaner combustion by increasing the availability of radicals such as OH, H, and O, which accelerate oxidation reactions and prevent soot precursor formation.

A positive effect of PM emissions was observed when co-firing HCNG with diesel. This is due to the effects described on the occasion of CO and HC – the mixture burns faster, is homogeneous and has a lower carbon ratio in favor of hydrogen. This is confirmed by other results in which the addition of hydrogen to CNG reduced the emission of both particulate matter and soot [36]. This is certainly also the result of the high degree of diffusivity of the water bottle, also resulting in the formation of a homogeneous mixture. The analysis of the chart leads to one more conclusion. For higher loads, the use of HCNG allowed to reduce PM emissions more significantly than at lower loads.

Mixing diesel, hydrogen and CNG as fuels in the engine resulted in an increase in NO_x

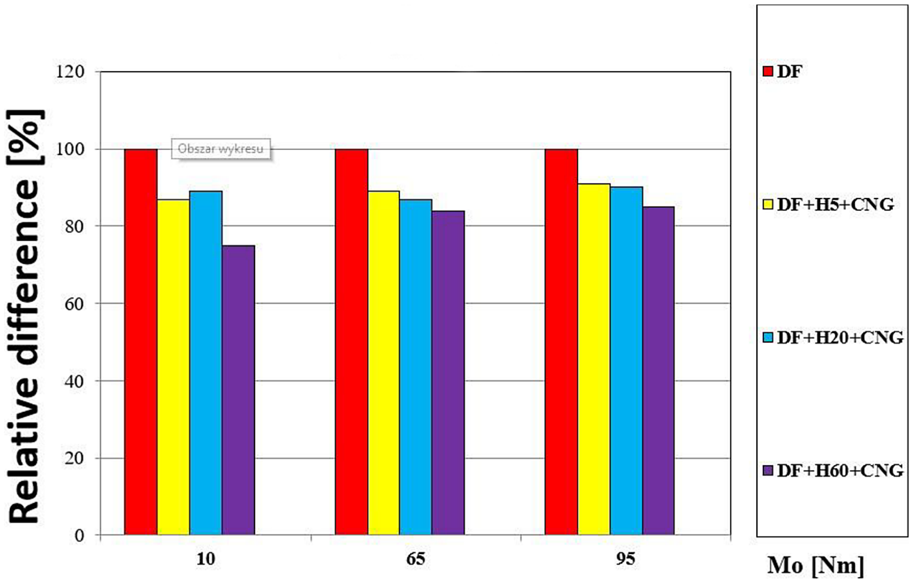

Figure 8. Relative difference of HC in load characteristic conditions for n = 1100 rpm

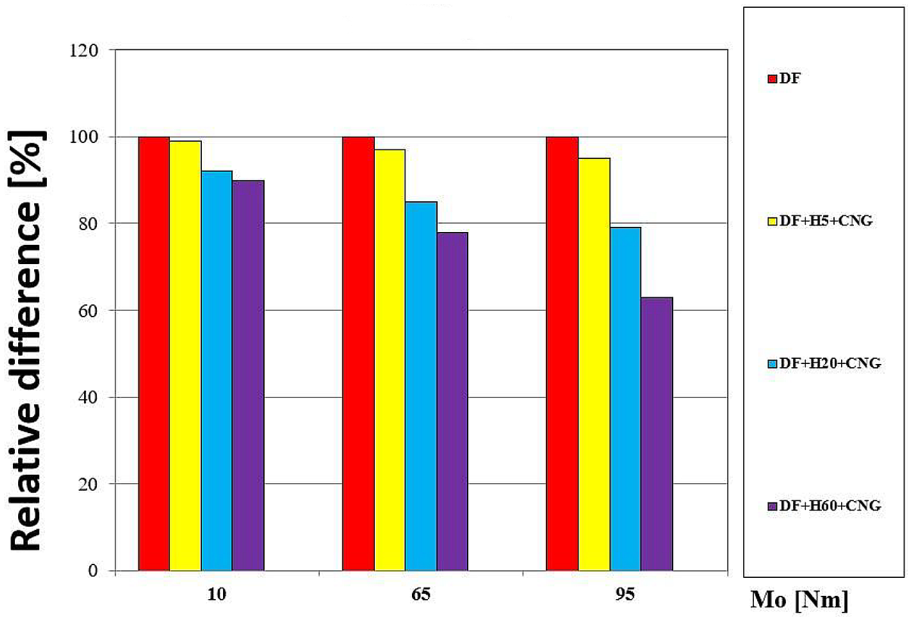

Figure 9. Relative difference of PM in load characteristic conditions for n = 1100 rpm

emissions. The nature of this process can be explained by linking factors including combustion characteristics, temperature and fuel composition. The emission results of NO_x are shown in Figure 10. In contrast, NO_x emissions increased with higher hydrogen content, particularly under elevated engine loads. At 95 Nm, the DF+H60+CNG blend resulted in up to a 60% increase in NO_x compared to pure diesel. This phenomenon is a result of increased combustion temperatures and excess oxygen availability in lean combustion environments.

As mentioned, hydrogen has a very high flame speed and burns at even higher temperatures than diesel. At the same time, diesel fuel has a high energy content and burns at high temperatures. Engines with CI operate at a high compression ratio, which leads to elevated combustion temperatures. The presence of hydrogen in the fuel mixture can significantly raise the peak combustion temperature. Although CNG burns cleaner than diesel, it can still contribute to higher combustion temperatures, especially when combined with other fuels. The formation of NO_x is largely temperature-dependent and occurs mainly through the thermal mechanism of NO_x, which involves the reaction of nitrogen and oxygen at high temperatures. Increased temperature in the combustion chamber (caused by the addition of hydrogen and the nature of diesel combustion) increases the rate of formation of thermal NO_x. In a diesel engine, especially with a mixture of hydrogen and CNG, there is usually excess oxygen during combustion. Excess oxygen allows the fuel to burn more completely, but it also provides a greater possibility of nitrogen reacting in the air with oxygen, creating NO_x. Adding hydrogen and CNG to a fuel mixture can create a poorer combustion environment, meaning there is more air (and thus more oxygen) relative to the amount of fuel. Poor mixtures usually burn warmer, which again promotes the formation of NO_x.

In turn, the high diffusivity of hydrogen and its rapid ignition properties lead to a faster and warmer combustion process. CNG, on the other hand, has a lower flash point and can burn completely in the presence of sufficient oxygen, contributing to higher combustion temperatures. Diesel fuel acts as the main source of ignition due to its self-ignition properties, ensuring complete combustion of the mixed fuel, but also contributing to high peak temperatures.

For example, lambda (λ) 1.6 indicates that the mixture is poor – the air to fuel ratio is 1.6 times greater than the stoichiometric ratio. This means that there is much more air (oxygen) than needed to burn the fuel completely. The high reactivity of hydrogen contributes significantly to the increase in peak combustion temperatures. CNG burns cleaner than diesel and has a higher combustion temperature. This usually results in a more complete combustion and a further increase in the combustion temperature. With a lambda value of 1.6, there is 60% more air in the combustion chamber than is required stoichiometrically, which provides sufficient oxygen for complete combustion. Excess oxygen leads to more efficient and warmer combustion, which promotes the formation of NO_x. Higher temperatures accelerate the mechanism of thermal NO_x formation, during which nitrogen in the air reacts with oxygen to form NO_x. Thermal NO_x is mainly formed by the reaction of nitrogen and oxygen at high temperatures. This is a critical process in combustion chemistry, particularly relevant in high-temperature combustion environments such as combustion engines. This is the dominant mechanism of NO_x production under conditions of high temperature and oxygen excess. Thermal NO_x refers to nitrogen oxides (NO and NO_2) formed when N_2 and O_2 in combustion air react at high temperatures. The rate of formation of thermal NO_x increases exponentially with temperature. This describes the Arrhenius equation, which shows that the reaction rate increases with temperature. The basic reactions associated with the thermal formation of NO_x are described by the

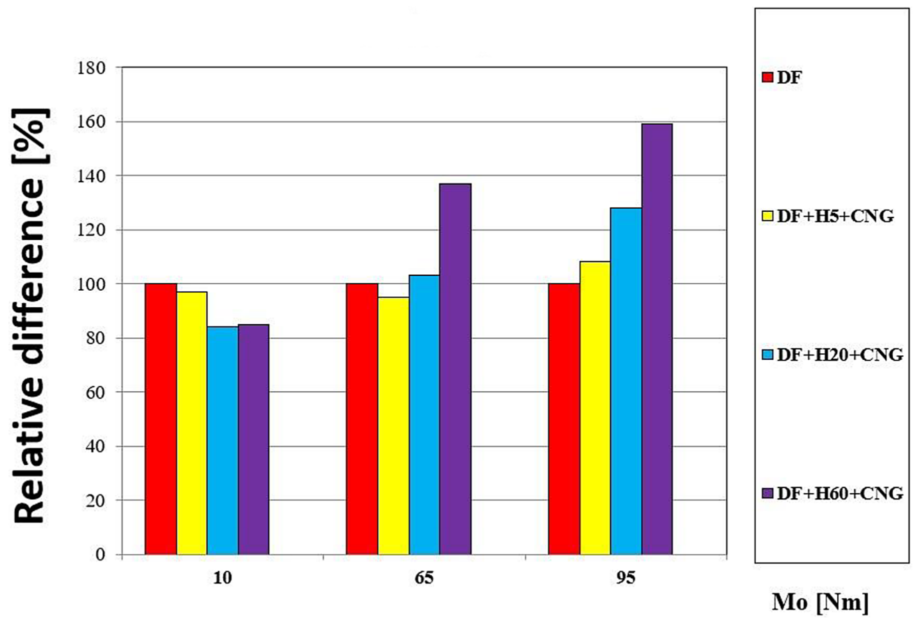

Figure 10. Relative difference of NO_x in load characteristic conditions for n = 1100 rpm

Zeldovich mechanism, which includes three main stages (free radical propagation reaction):
Reaction1: Formation of Nitric Oxide (NO):

$$N_2 + O \rightarrow NO + N \quad (1)$$

This reaction is endothermic and requires high temperatures to proceed efficiently. Oxygen atoms (O) are produced from the dissociation of O_2 at high temperatures.
Reaction 2: Formation of nitric oxide (NO):

$$N + O_2 \rightarrow NO + N \quad (2)$$

This reaction is exothermic and further propagates the formation of NO by recycling oxygen atoms.
Reaction 3: Formation of nitrogen dioxide (NO_2):

$$NO + O \rightarrow NO_2 \quad (3)$$

This reaction can convert NO to NO_2 but it typically occurs at lower temperatures in the post-combustion region.

In addition to the Zeldovich mechanism, several supplementary radical reactions also play a critical role in emissions dynamics with HCNG blends:

$$H_2 + O \rightarrow OH + H \quad (4)$$

Generates highly reactive OH radicals, essential for oxidizing CO and HC.

$$H + O_2 \rightarrow OH + O \quad (5)$$

Produces further oxidizing species, enhancing combustion efficiency.

$$CO + OH \rightarrow CO_2 + H \quad (6)$$

Facilitates oxidation of CO into CO_2.

$$RH + OH \rightarrow R\bullet + H_2O \quad (7)$$

Initiates hydrocarbon oxidation by hydrogen abstraction. These chain-propagating reactions are significantly accelerated by hydrogen's presence, supporting complete combustion and reducing CO, HC, and PM emissions.

However, the trade-off with increased NO_x emissions suggests a need for optimization strategies such as:

- Exhaust gas recirculation (EGR) to lower peak combustion temperatures.
- After-treatment systems like selective catalytic reduction (SCR).
- Lambda control to dynamically adjust air-fuel ratios depending on operating conditions

The effect of higher pressure in the combustion chamber, which also leads to higher combustion temperatures, should also be considered. This is because the temperature in the combustion chamber is directly proportional to the pressure (described by the law of perfect gas). Higher pressures improve the efficiency of the combustion process, ensuring a more complete combustion of the fuel mixture. While this improves output power, it also results in higher peak temperatures. At higher pressures, fuel and air mix more thoroughly, leading to more efficient combustion. This thorough mixing ensures the complete combustion of more fuel, which again leads to higher combustion temperatures.

Higher engine torque requires more power, which is achieved by injecting more fuel into the combustion chamber. As more fuel is burned, the combustion temperature increases, which contributes to increased NO_x formation. As the load and torque of the engine increase, so does the pressure and temperature in the combustion chamber. Higher combustion temperatures and pressures lead to more intense thermal NO_x formation, as the NO_x formation rate is very temperature sensitive. At higher loads, the motor operates at higher pressures and temperatures to meet the increased power demand. Under these conditions, combustion efficiency improves, but the disadvantage is the increase in thermal NO_x production as a result of elevated temperatures.

The characteristics of fast hydrogen combustion and the high energy content of diesel fuel result in efficient but high-temperature combustion processes. Several strategies can be used to mitigate the increase in NO_x emissions:

- Exhaust gas recirculation (EGR): Returns some of the exhaust gas back to the combustion chamber, lowering the peak combustion temperatures and thus reducing the formation of NO_x.
- Selective catalytic reduction (SCR): Uses a catalyst to convert NO_x in the exhaust gas to nitrogen and water.
- Lean NO_x traps (LNTs): absorb NO_x in poor conditions and release it in rich conditions where it can be reduced to nitrogen.
- Combustion Time and Fuel Injection Strategies: Optimizing the timing and method of fuel injection can help control combustion temperatures and reduce NO_x formation.

By understanding these factors and using appropriate strategies, it is possible to manage and minimize the increase in NO_x emissions from engines using a mixture of diesel, hydrogen and CNG.

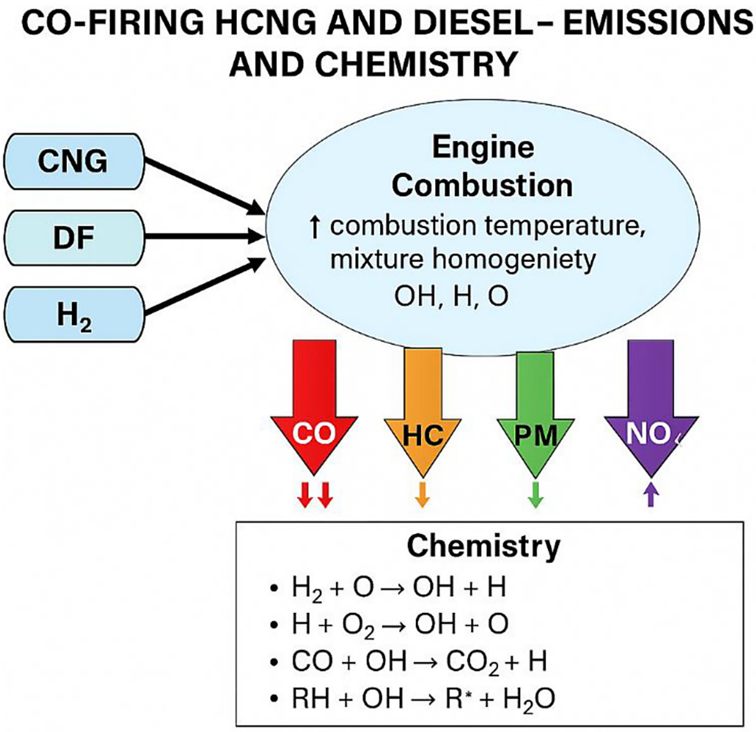

Figure 11. Schematic diagram that visually supports the emission mechanisms

CONCLUSIONS

Studies have shown the positive impact of using hydrogen from CNG, referred to as HCNG, when co-firing diesel in a diesel engine. This effect results from the association of the unfavorable properties of CNG with the unique properties of hydrogen. The use of hydrogen shortens the burning time due to the high speed of the flame. The range of flammability of the fuel mixture increases. Hydrogen as a gas is characterized by high diffusivity which makes it possible to achieve greater homogeneity of the fuel mixture. It also has a higher auto-ignition temperature than CNG, which also leads to better combustion. HCNG thus combines the advantages of a safe, slow-burning fuel like CNG with an efficient, fast-burning fuel like hydrogen. With this concept, CNG acts as the primary energy carrier and stabilizer of the combustion process. Faster and more complete combustion of hydrogen and CNG also increases the thermal efficiency of the engine. Setting parameters of the SB 3.1 engine fueled by diesel fuel and hydrogen addition. Schematic diagram of the results that visually supports the emission mechanisms is shown on Figure 11.

The authors showed that the use of HCNG can mitigate harmful emissions from CI engines, including CO, CH, PM. NO_x emission looked less favorable. Key learning points:

Co-firing diesel with HCNG (a mixture of hydrogen and CNG) effectively reduces CO emissions. Hydrogen, thanks to the lack of carbon and high combustion rate, intensifies the combustion process, improving its efficiency and reducing CO emissions. Its high diffusivity unifies the fuel mixture and also promotes chemical reactions, increasing the stability of methane combustion. Higher hydrogen content in HCNG further enhances these effects, improving combustion and reducing CO.

The positive effect of HCNG on hydrocarbon emissions results from replacing coal with hydrogen, which increases the H/C ratio and reduces carbon-related emissions. Hydrogen improves the combustion rate and compensates for effects such as ignition delay or low speed of the CNG flame. Thanks to this, HCNG more effectively reduces the negative impact of wall and gap phenomena that cause uneven combustion at the walls and in the engine gaps. At higher engine loads, combustion stability increased, leading to more efficient combustion and further reduction of HC emissions. At low loads, these effects are less visible due to the combustion of lean mixtures.

Co-combustion of HCNG with diesel effectively reduces PM emissions. This is due to faster and more homogeneous combustion and a reduction in the carbon ratio in favor of hydrogen. Hydrogen, thanks to its high diffusivity, promotes the formation of a homogeneous mixture, which reduces PM and soot emissions. PM emission reductions have been shown to be more noticeable at lower engine loads than at higher ones.

The presence of hydrogen and CNG in the diesel fuel mixture in the diesel engine raises the combustion temperature, which promotes the formation of NO_x. Hydrogen, thanks to its high flame speed and faster ignition, intensifies the combustion process, increasing peak temperatures. CNG burns cleaner than diesel, but it also increases the combustion temperature. Excess oxygen in the lean mixture (e.g. at $\lambda = 1.6$) ensures full combustion, but also intensifies the formation of thermal NO_x as a result of the reaction of nitrogen with oxygen at high temperatures, according to the Zeldovich mechanism. Higher temperatures and excess oxygen accelerate this process, making it dominant in HCNG diesel engines.

- HCNG is a promising transitional fuel blend for reducing carbon-based emissions.
- Emissions can be tuned through hydrogen dosing, offering flexibility for meeting different regulatory targets.
- With proper after-treatment technologies, the adverse effect on NO_x can be mitigated.

REFERENCES

1. International Energy Agency. World Energy Outlook 2024 [Internet]. Paris: IEA; October 2024 [cited 2025 Jun 11]. Available from: https://www.iea.org/reports/world-energy-outlook-2024
2. Milewicz J, Mokrzan D, Szymański GM. Environmental impact evaluation as a key element in ensuring sustainable development of rail transport. Sustainability. 2023;15(18):13754. https://doi.org/10.3390/su151813754
3. Ulbrich D, Kowalczyk J, Jósko M, Sawczuk W, Chudyk P. Assessment of selected properties of varnish coating of motor vehicles. Coatings. 2021;11(11):1320. https://doi.org/10.3390/coatings11111320
4. Zhang Y, Zhong Y, Lu S, Zhang Z, Tan D. A comprehensive review of the properties, performance, combustion, and emissions of the diesel engine fueled with different generations of biodiesel. Processes. 2022;10(6):1178. https://doi.org/10.3390/pr10061178
5. Lijewski P, Kozak M, Fuć P, Ziółkowski A. Exhaust emissions generated under actual operating conditions from a hybrid vehicle and an electric one fitted with a range extender. Transp Res Part D: Transp Environ. 2020;78:102183. https://doi.org/10.1016/j.trd.2019.11.012
6. Rymaniak Ł, Lijewski P, Kamińska M, Fuć P, Kurc B, Siedlecki M, Kalociński T, Jagielski A. The role of real power output from farm tractor engines in determining their environmental performance in actual operating conditions. Computers and Electronics in Agriculture. 2020;173:105405. https://doi.org/10.1016/j.compag.2020.105405
7. Pielecha J, Skobiej K, Kubiak P, Wozniak M, Siczek K. Exhaust emissions from plug-in and HEV vehicles in type-approval tests and real driving cycles. Energies. 2022;15(7):2423. https://doi.org/10.3390/en15072423
8. Ciesielski R, Zakrzewski M, Shtyka O, Maniecki T, Rylski A, Wozniak M, Kubiak P, Siczek K. The research on characteristics of CI engine supplied with biodiesels from brown and yellow grease. Energies. 2022;15(11):4083. https://doi.org/10.3390/en15114083
9. Ziółkowski A, Fuć P, Jagielski A, Bednarek M. Analysis of emissions and fuel consumption in freight transport. Energies. 2022;15(13):4706. https://doi.org/10.3390/en15134706
10. Directorate General for Climate Action, European Commission. CO_2 emission performance standards for cars and vans [Internet]. Luxembourg: Publications Office of the European Union; 2023 Dec 19 [cited 2025 Jun 11]. Available from: https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/co2-emission-performance-standards-cars-and-vans_en
11. European Environment Agency. CO_2 performance emissions of new vans in Europe [Internet]. Copenhagen: EEA; 2024 Dec 16 [cited 2025 Jun 11]. Available from: https://www.eea.europa.eu/en/analysis/indicators/co2-performance-emissions-of-new
12. Kowalczyk J, Matysiak W, Sawczuk W, Wieczorek D, Sędłak K, Nowak M. Quality tests of hybrid joint–clinching and adhesive – case study. Appl Sci. 2022;12(22):11782. https://doi.org/10.3390/app122211782
13. Komorski P, Szymański GM, Nowakowski T. Development of the urban rail vehicle acoustic model. Applied Acoustics. 2022;195:108807. https://doi.org/10.1016/j.apacoust.2022.108807
14. Reitz RD, Ogawa H, Payri R, Fansler T, Kokjohn S, Moriyoshi Y, et al. IJER editorial: The future of the internal combustion engine. International Journal of Engine Research. 2020;21(1):3–10. https://doi.org/10.1177/1468087419877990
15. Kamińska M, Rymaniak Ł, Daszkiewicz P, Lijewski P. Test Guidelines for Evaluation Real Driving Emission Two-Way Vehicles. MATEC Web

Conf. 2019;294:02009. https://doi.org/10.1051/matecconf/201929402009

16. Abdul Manan AFN, Gordillo Zavaleta V, Agarwal AK, Kalghatgi G, Amer AA. Electrifying passenger road transport in India requires near term electricity grid decarbonisation. Nat Commun. 2022;13(1):2095. https://doi.org/10.1038/s41467-022-29620-x
17. Kalghatgi G. Is it the end of combustion and engine combustion research? Should it be? Transportation Engineering. 2022;10:100142. https://doi.org/10.1016/j.treng.2022.100142
18. Quadri SAP, Rentala GS, Sarap R. Performance, combustion and exhaust emissions analysis of HCNG fuelled single cylinder diesel engine at different injection opening pressures. World J Eng. 2018;15(6):710–718. https://doi.org/10.1108/WJE 03 2017 0054
19. Pielecha I, Szwajca F, Skobiej K, Pielecha J, Merkisz J, Cieslik W. Analysis on monofuel: Methane and hydrogen in passive TJI engine using Center of Combustion and λ value control. Int J Hydrogen Energy. 2024;83:1170–1183. https://doi.org/10.1016/j.ijhydene.2024.08.159
20. Bari S, Hossain SN. Performance of a diesel engine run on diesel and natural gas in dual fuel mode of operation. Energy Procedia. 2019;160:215–222. https://doi.org/10.1016/j.egypro.2019.01.115
21. Muralidharan M, Srivastava A, Subramanian M. A technical review on performance and emissions of compressed natural gas – diesel dual fuel engine. SAE Technical Paper 2019 28 2390. Warrendale (PA): SAE International; 2019 Nov 21; 17. https://doi.org/10.4271/2019 28 2390
22. Li J, Huang H, Chen G, Liang J D, Cai X, Chen S, Sun Y. Prediction and verification of performance and emission characteristics of diesel/natural gas dual fuel engine based on intelligent algorithm. ACS Omega. 2023;8(20):18212–18224. https://doi.org/10.1021/acsomega.3c01636
23. Wei L, Geng P. A review on natural gas/diesel dual fuel combustion, emissions and performance. Fuel Process Technol. 2016;142:264–278. https://doi.org/10.1016/j.fuproc.2015.09.018
24. International Renewable Energy Agency (IRENA). Hydrogen [Internet]. Abu Dhabi: IRENA; [cited 2025 Jun 11]. Available from: https://www.irena.org/Energy-Transition/Technology/Hydrogen
25. Rueda Vázquez JM, Serrano J, Pinzi S, Jiménez Espadafor FJ, Dorado MP. A review of the use of hydrogen in compression ignition engines with dual fuel technology and techniques for reducing NO_x emissions. Sustainability. 2024;16(8):3462. https://doi.org/10.3390/su16083462
26. Stępień Z. A comprehensive overview of hydrogen-fueled internal combustion engines: achievements and future challenges. Energies. 2021;14(20):6504. https://doi.org/10.3390/en14206504
27. Szwaja S, Grab Rogalinski K. Hydrogen combustion in a compression ignition diesel engine. Int J Hydrogen Energy. 2009;34(10):4413–4421. https://doi.org/10.1016/j.ijhydene.2009.03.020
28. Nelsson C, Hulteberg C, Saint Just J, Kaiadi M. HCNG – A Dead End or a Bridge to the Future? In: Proceedings of the 18th World Hydrogen Energy Conference; 2010 May 16–21; Essen, Germany. Essen: WHEC; 2010.
29. Ajmeri KH, Sharma S, Shishodia D, Sharma S, Singh S. Review on possibility to run the diesel engine on HCNG fuel. Int J Res Anal Rev [Internet]. 2020 Mar;7(1):79–87
30. Subramanian M. Performance Analysis of 18% HCNG fuel on Heavy Duty Engine. SAE Technical Paper 2014 01 1453. Warrendale (PA): SAE International; 2014; 10. https://doi.org/10.4271/2014 01 1453
31. Thipse SS, Rairikar SD, Kavathekar KP, Chitnis PP. Development of a six cylinder HCNG engine using an optimized lean burn concept. SAE Technical Paper 2009 26 0031. Warrendale (PA): SAE International; 2009. https://doi.org/10.4271/2009 26 0031
32. Zhou J, Cheung C, Leung C. Combustion, performance and emissions of a diesel engine with H_2, CH_4 and H_2–CH_4 addition. International Journal of Hydrogen Energy. 2014;39(10):4611–4621. https://doi.org/10.1016/j.ijhydene.2013.12.194
33. Vadlamudi S, Gugulothu SK, Panda JK, Deepanraj B, Kumar PRV. Paradigm analysis of performance and exhaust emissions in CRDI engine powered with hydrogen and hydrogen/CNG fuels: a green fuel approach under different injection strategies. Int J Hydrogen Energy. 2023;48(96):38059–38076. https://doi.org/10.1016/j.ijhydene.2022.08.277
34. Saravanan N, Nagarajan G. Experimental investigation in optimizing the hydrogen fuel on a hydrogen diesel dual fuel engine. Energy Fuels. 2009;23(5):2646–2657. https://doi.org/10.1021/ef801097s
35. Abu Mansor MR, Abbood MM, Mohamad TI. The influence of varying hydrogen methane diesel mixture ratio on the combustion characteristics and emissions of a direct injection diesel engine. Fuel. 2017;190:281–291. https://doi.org/10.1016/j.fuel.2016.11.010
36. Karagöz Y, Güler İ, Sandalcı T, Yüksek L, Dalkılıç AS, Wongwises S. Effects of hydrogen and methane addition on combustion characteristics, emissions, and performance of a CI engine. International Journal of Hydrogen Energy. 2016;41(2):1313–1325. https://doi.org/10.1016/j.ijhydene.2015.11.112