energies

MDPI

Article

Co-Combustion of Hydrogen with Diesel and Biodiesel (RME) in a Dual-Fuel Compression-Ignition Engine

Wojciech Tutak *, Arkadiusz Jamrozik and Karol Grab-Rogaliński

Department of Thermal Machinery, Czestochowa University of Technology, 42-201 Czestochowa, Poland
* Correspondence: wojciech.tutak@pcz.pl

Abstract: The utilization of hydrogen for reciprocating internal combustion engines remains a subject that necessitates thorough research and careful analysis. This paper presents a study on the co-combustion of hydrogen with diesel fuel and biodiesel (RME) in a compression-ignition piston engine operating at maximum load, with a hydrogen content of up to 34%. The research employed engine indication and exhaust emissions measurement to assess the engine's performance. Engine indication allowed for the determination of key combustion stages, including ignition delay, combustion time, and the angle of 50% heat release. Furthermore, important operational parameters such as indicated pressure, thermal efficiency, and specific energy consumption were determined. The evaluation of dual-fuel engine stability was conducted by analyzing variations in the coefficient of variation in indicated mean effective pressure. The increase in the proportion of hydrogen co-combusted with diesel fuel and biodiesel had a negligible impact on ignition delay and led to a reduction in combustion time. This effect was more pronounced when using biodiesel (RME). In terms of energy efficiency, a 12% hydrogen content resulted in the highest efficiency for the dual-fuel engine. However, greater efficiency gains were observed when the engine was powered by RME. It should be noted that the hydrogen-powered engine using RME exhibited slightly less stable operation, as measured by the COV_{IMEP} value. Regarding emissions, hydrogen as a fuel in compression ignition engines demonstrated favorable outcomes for CO, CO_2, and soot emissions, while NO and HC emissions increased.

Keywords: dual-fuel; diesel; hydrogen; RME; combustion; emission

Citation: Tutak, W.; Jamrozik, A.; Grab-Rogaliński, K. Co-Combustion of Hydrogen with Diesel and Biodiesel (RME) in a Dual-Fuel Compression-Ignition Engine. *Energies* **2023**, *16*, 4892. https://doi.org/10.3390/en16134892

Academic Editors: Enzo Galloni and Davide Lanni

Received: 4 June 2023
Revised: 18 June 2023
Accepted: 21 June 2023
Published: 23 June 2023

1. Introduction

Due to their high efficiency, durability, and reliability, compression-ignition internal combustion engines are widely utilized to power various machines and generators [1]. However, these engines are also recognized as significant sources of environmental pollution, including emissions of NOx and soot [2]. In order to address health concerns and ensure air quality, stringent regulations have been implemented to limit exhaust emissions from these engines [3]. Over the years, extensive efforts have been made to mitigate the impact of human activities on the natural environment and combat global warming. One area of focus has been the exploration of alternative fuels as substitutes for petroleum-derived fuels, aiming to reduce exhaust emissions, achieve energy independence from fossil fuels, and diversify energy sources. Research is actively conducted on clean combustion systems and low-emission fuels. Hydrogen, as a carbon-free fuel that does not produce solid particles, hydrocarbons, or carbon oxides, has emerged as an appealing option for powering reciprocating engines [4]. However, hydrogen alone is not suitable for self-sustained combustion in compression-ignition engines due to its high self-ignition temperature and low cetane number. The combustion of hydrogen can result in significant increases in pressure and temperature, potentially leading to knocking combustion in the engine's combustion chamber and increased NOx emissions [5]. Therefore, in compression-ignition engines, hydrogen is co-combusted with diesel or biodiesel in a dual-fuel configuration. Typically, hydrogen is introduced into the intake system, and its mixture with air is ignited by a dose of liquid fuel injected directly into the engine's combustion chamber [6]. The ignition of hydrogen requires a smaller ignition dose, and due to its rapid combustion rate, the mixture in the combustion chamber is quickly consumed [7]. Many research studies have utilized hydrogen to shorten the combustion time and reduce the carbon-to-hydrogen (C/H) ratio, thereby significantly influencing engine exhaust emissions [8]. The high diffusivity of hydrogen positively impacts mixture homogeneity and the combustion process. However, in a dual-fuel engine where hydrogen is the primary fuel introduced into the intake manifold, the volumetric efficiency of the engine decreases as a portion of the air volume is replaced by hydrogen. This can be a limitation for high engine loads [9]. Biodiesel, on the other hand, is considered a potential replacement for diesel fuel in compression ignition engines. With its oxygen content in the molecular structure, biodiesel is regarded as a more environmentally friendly fuel. It can be produced through the chemical processing of both edible and inedible vegetable oils and animal fats [10]. However, biodiesel also has drawbacks such as a lower calorific value (LHV) and higher viscosity, which can impact the engine's fuel system [11].

Numerous studies have been conducted in the literature regarding the co-combustion of liquid fuels with hydrogen in compression ignition engines. Kanth and Debbarma [12] examined the co-combustion of hydrogen with diesel fuel and a mixture of diesel fuel and biodiesel. They observed a 2.5% increase in engine efficiency when fueled with diesel fuel and hydrogen, and a 1.6% increase when co-combusting with a mixture of diesel fuel and biodiesel (10% v/v). Additionally, there was a reduction in CO emissions (~30%) and UHC, but an increase in NOx emissions. Gomes Antunes et al. [13] investigated a dual-fuel engine powered by diesel and hydrogen, with both fuels injected directly into the combustion chamber. They achieved a 14% increase in engine power, but heating of the intake air was necessary for stable operation. Significant pressure increases during combustion were observed, accompanied by a significant improvement in engine efficiency. Liu et al. [14] also examined a dual-fuel compression-ignition engine utilizing direct hydrogen injection. They determined that the maximum energy share of hydrogen is 50%, and the co-combustion process with diesel fuel can be controlled within this range. It is crucial to inject hydrogen into the cylinder early enough to form a flammable mixture with air. Tests conducted with hydrogen injection ranging from 180 to 20 deg bTDC indicated that injecting hydrogen from 40 to 20 deg bTDC resulted in decreased engine efficiency, IMEP (Indicated Mean Effective Pressure), increased soot and CO emissions, likely due to insufficient time for mixture formation. Muralidhara et al. [15] presented the influence of hydrogen co-combustion with biodiesel on compression ignition engine parameters. Hydrogen was introduced into the intake manifold, and they observed a decrease in engine efficiency with an increase in hydrogen content. Akar et al. [16] employed hydrogen to enhance the combustion process during the disposal of biodiesel from waste oil transesterification. The addition of hydrogen positively affected engine performance and reduced emissions of toxic exhaust components, excluding NOx. Köse and Acaroğlu [17] investigated the effect of varying proportions of hydrogen co-combusted with diesel fuel, biodiesel, and a mixture of diesel fuel and biodiesel at low hydrogen concentrations. They found that the diesel-biodiesel mixture with 2.5% hydrogen resulted in the highest power output, while the greatest efficiency was achieved by the engine fueled solely by biodiesel with 2.5% hydrogen. Tutak et al. [18] studied the impact of enriching CNG with hydrogen on engine parameters and exhaust emissions. They established that a dual-fuel engine operated stably when powered by 90% CNG and 10% diesel fuel, with hydrogen replacing a portion of the CNG. The inclusion of hydrogen enhanced the combustion process, accelerating it and increasing engine efficiency. Up to nearly 20% of the energy share of hydrogen, there were no adverse effects on engine stability, and CO emissions from the exhaust gas were practically eliminated.

A synthetic summary of the results obtained by various authors is included in Table 1. Table 1 displays the effect of hydrogen on performance, emission and combustion parameters of hydrogen with diesel and biodiesel.

Table 1. Performance, emission and combustion characteristics of hydrogen with diesel or biodiesel.

Ref.	Engine Type	Fuelling Type	Operating Parameters	Emission
[6]	1-cylinder, 4-stroke, water cooled engine, constant speed 1500 rpm	diesel fuelling, dose of hydrogen into engine manifolds, hydrogen energy share: 0%, 5%, 10%, 20%	load (25, 50 and 75%), increase of COV_{IMEP} at 25% load, stabilization and increase of COV_{IMEP} at 50 and 75% load	decrease of unregulated emissions (formaldehyde and acetaldehyde), (propylene, ethylene and aromatic hydrocarbons)
[9]	1-cylinder (normally aspirated, air-cooled). engine speed at 1500 rpm	hydrogen into the intake manifold, hydrogen energy share (HES): 0% (100% diesel), 6%, 12%, 18% and 24%	5.2% decrease at 24% HES in the BSEC, BTE increase (by 7.85% with 24% HES)	NOx increase (3.42%), CO_2 (3.61%), CO (2.84%), and smoke (4.85%) decrease
[12]	1-cylinder, 4-stroke, naturally aspired, constant speed 1500 rpm	diesel and biodiesel, hydrogen at a fixed flow rate of 7 lpm through the intake manifold, hydrogen-enriched diesel (D + H2), hydrogen-enriched 10, and 20% rice bran biodiesel blend (RB10 + H2)	engine load: 30%, 50%, 70%, 80%, 90%, 100%, 1.6% increase in the brake thermal efficiency, 6.35% decrease in fuel consumption	4–38% lower CO emissions, 6–14% lower UHC emission, 6–13% higher NOx emission
[13]	single cylinder, constant engine speed, four-stroke, direct injection, naturally aspirated, air-cooled	conventional diesel, direct injection hydrogen-fuelled mode, varying the excess air ratio	higher power to weight ratio, 14% higher peak power, 43% fuel efficiency (28% for diesel engine)	20% reduction in NOx emission
[14]	automotive-size, 1-cylinder, common-rail	hydrogen-diesel dual-fuel engine with dual direct injection, hydrogen energy fractions (0–50%)	intermediate fixed load of about 7.8 bar IMEP, indicated efficiency of 47% at 50% hydrogen substitution ratio	NOx emission below11 g/kWh
[15]	1-cylinder, water cooled engine, constant speed 1500 rpm	B100 + hydrogen (variable ratio) hydrogen into the intake manifold, hydrogen-enriched biodiesels, flow rates of H_2 from 0.1 to 0.25 kg/h	80% and 100% load reduction of brake thermal efficiency (BTE)	reduction of smoke, CO and HC emissions, increase NOx
[16]	naturally aspirated, water cooled, four stroke, 1-cylinder	B100 blended with diesel: 10 and 20%, pure hydrogen to intake manifold	B100 fraction deteriorated performance, Hydrogen improved performance	B100 fraction deteriorated emission, decrease CO and CO_2, increase of NOx
[17]	4-cylinder, turbocharged, variable rpm	small dose of hydrogen into intake manifold, D100, B100, (B7 + H2.5), (D + H2.5); D100/B100 blends direct inj.	max power and torque for (B7 + H2.5), highest ITE (B100 + H2.5)	reduction HC; increase NOx, minimum CO for B100 and (B100 + H2.5)
[19]	4-cylinder, water cooled, engine speeds ranging from 1200 to 2800 rpm	hydrogen into the intake manifold hydrogen-enriched pomegranate seed oil biodiesel (POB), hydrogen flow: 5 L/min	full load conditions, positive effects on power output and BSFC	improvement of CO emissions, deterioration of NOx emissions

Table 1. *Cont.*

Ref.	Engine Type	Fuelling Type	Operating Parameters	Emission
[20]	4-cylinder, heavy-duty, (EGR) system and a boosting system	H2 energy share ratio of up to 98%	low and medium operating loads	for low load: reduction of CO and NOx emission of over 90%, soot decrease by 85%, for medium load increase NOx emission
[21]	four-stroke, water cooled, 4-cylinder, turbocharger, engine speeds 1000 to 2500 rpm	hydrogen into the inlet manifold (2.5%, 5% and 7.5% as volume)	full load, increase in engine torque, power, thermal efficiency, nitrogen oxides (NOx) and exhaust gasses temperatures	increase in NOx and EGT, decrease in HC, CO
[22]	1-cylinder, four-stroke, water cooled, 4-cylinder, 1500 rpm	hydrogen into the inlet manifold (constant fraction 25%) biodiesel	full range of load, small increase in BTE	decrease in CO, CO_2, HC and NOx
[23]	1-cylinder, four-stroke, water cooled	diesel and biodiesel, hydrogen flow into intake manifold 7 lpm	small increase in BTE	reduction in HC, CO and smoke, increase in NOx
[24]	1-cylinder, water cooled, 1500 rpm	diesel and palm biodiesel blend (P20), hydrogen injected into the intake manifold at different flow rates of 7 lpm and 10 lpm, loading condition of 30%, 60%, 80%, 90%, and 100%	increase in BTE and decrease in BSEC, reduction in combustion duration (CD), best improvement achieved for 90% load.	increase in NOx, decrease in CO, CO_2 and HC, At 90% load, 10 lpm of H2-decreased HC od 51% and CO of 37%

The literature on co-combustion of hydrogen with liquid fuels in dual-fuel engines highlights the positive impact of hydrogen on engine performance and exhaust emissions. Various types of liquid fuels, including diesel and biodiesels, are utilized. As shown in Table 1, the obtained results on different types of engines, under various conditions and operating points, often yield divergent outcomes. Each research setup and experimental procedure are to some extent distinct, and the results are often incomparable in terms of values. Both single-cylinder and multi-cylinder engines, naturally aspirated and turbocharged, are utilized in optimizing the combustion process or under constant settings. The study presents the results of a comparative analysis of the combustion process in an engine fueled by diesel fuel and hydrogen, as well as RME and hydrogen under very similar conditions on the same engine. The obtained results for both analyzed cases are fully comparable, reflecting the influence of fuel type on engine performance parameters and emissions over a wide range of hydrogen proportions. An estimation of variations in the occurrence of characteristic stages of combustion is provided. In the cited works in the Introduction, as well as in many others, angles are determined for ID (Ignition Delay), CD (Combustion Duration), and CA50 (Crank Angle at 50% heat release) for average combustion profiles from the dataset. This study includes a statistical analysis for these combustion stages.

This paper aims to provide a comparative analysis of the combustion process in a dual-fuel compression-ignition engine operating at maximum load, using hydrogen with diesel fuel and hydrogen with biodiesel (specifically, Rapeseed Methyl Esters-RME). The results presented demonstrate the variations in engine operation based on the specific liquid fuel co-combusted with hydrogen. For both examined scenarios, the same proportion of hydrogen was employed relative to the liquid fuel (4%, 7%, 12%, 23%, and 34%). The impact of hydrogen content on heat release, characteristic combustion stages, and exhaust emissions was evaluated.

2. Materials and Methods

The study on the co-combustion of hydrogen with diesel fuel and biodiesel (RME) was conducted on a test bench, primarily consisting of a single-cylinder, naturally aspirated, four-stroke, air-cooled diesel engine. The engine was coupled with a DC generator, which ensured a stable rotational speed and facilitated continuous measurement and control of the engine's load. The engine was specifically designed to operate at a constant speed under a consistent maximum load. To enable the co-combustion of the two fuels, an additional gas supply system was installed in the engine, injecting the gas into the intake manifold, with pressure control, thereby transforming it into a dual-fuel engine. The technical specifications of the test engine are presented in Table 2.

Table 2. Main technical specifications of the test engine.

Item	Title 2
Engine model	Andoria 1CA90
Type of engine	Stationary, four stroke
Type of ignition	Compression ignition
Rated speed (rpm)	1500
Engine rated power @1500 rpm (kW)	7
Technique of cooling	Air cooled
Intake system	Naturally aspirates
Bore/stroke (mm)	90/90
Displacement (cc)	573
No. of cylinders	1
Injection system	Direct injection
Compression ratio	17
Start of injection (deg bTDC)	20

In addition to the engine, the test setup included various components: a system for measuring and recording in-cylinder pressure using a Kistler 6061 pressure sensor, a Kistler 5011 charge amplifier, and a Measurement Computing USB-1608HS data acquisition card. The rotational speed was stabilized, measured, and recorded using a dedicated system. The power supply systems incorporated both liquid fuels (diesel and biodiesel) and gaseous fuel (hydrogen). Liquid fuel consumption was measured using a dedicated measurement system, while hydrogen and air consumption were monitored using Common CGR-01 gas rotor flow meters. An exhaust gas analyzer set, consisting of a Bosch five-gas exhaust gas analyzer Bosch BEA 350 and an opacimeter AVL 415SE, was employed. Figure 1 illustrates the test setup diagram, depicting the test engine and the accompanying measuring equipment.

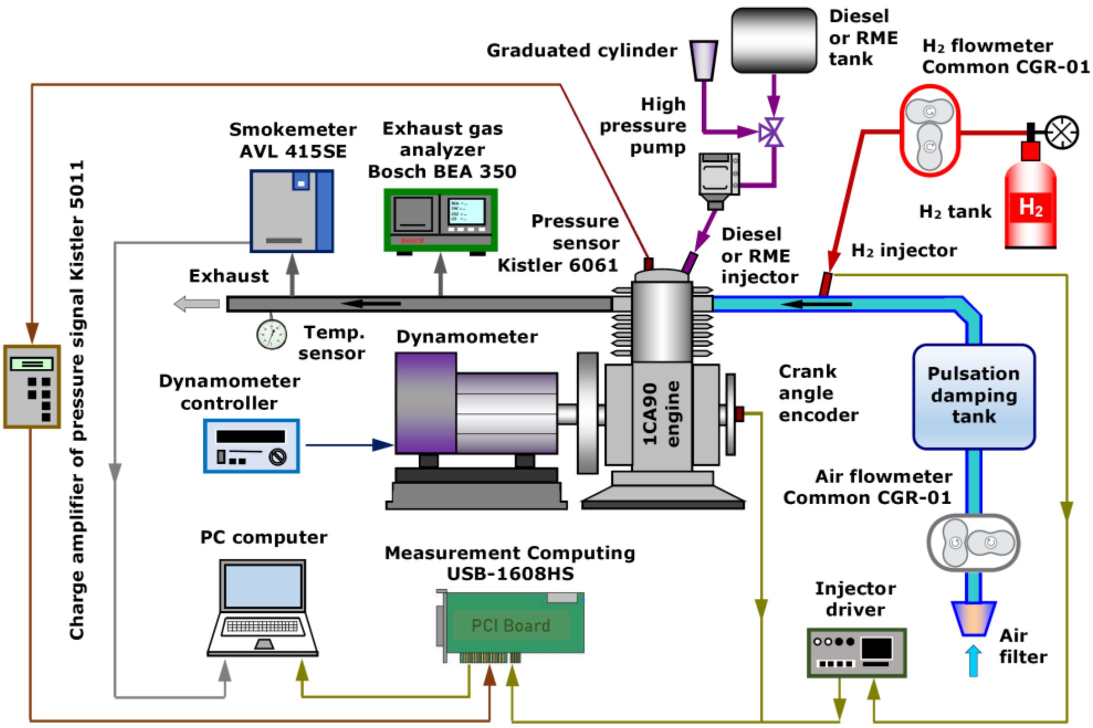

Figure 1. Diagram of the test stand with measuring equipment.

The study used the following measurement apparatus:

- pressure sensor Kistler 6061, range 0 . . . 250 bar, linearity < ±0.5% FS,
- charge amplifier Kistler 511, range ±10 . . . ±999,000 pC for 10 V FS, error < ±3%, linearity < ±0.05% FS,
- data acquisition module, Measurement Computing USB-1608HS-16 bits resolution, sampling frequency 20 kHz with software,
- air rotor flowmeter Common CGR-01 G40 DN50, measuring range 0.65 . . . 65 m^3/h, accuracy class 1,
- CNG rotor flowmeter Common CGR-01 G10 DN50, measuring range 0.25 . . . 25 m^3/h, accuracy class 1,
- Bosch BEA 350 analyzer.

Table 3 presents the characteristics of the exhaust gas analyzer, its measurement ranges and accuracy.

Table 3. Parameters of the Bosch BEA 350 analyzer.

Apparatus	Measuring Range	Resolution	Accuracy from Measured Value	Absolute Accuracy
CO	0.000–10.000% vol. 0.000–5.000% vol.	0.001% vol. 0.001% vol.	... ±5%	... ±0.06% vol.
HC	0–9999 ppm vol. 0–2000 ppm vol.	1 ppm vol. 1 ppm vol.	... ±5%	... ±12 ppm vol.
CO_2	0.00–18.00% vol. 0.00–16.00% vol.	0.01% vol. 0.01% vol.	... ±5%	... ±0.5% vol.
O_2	0.00–22.00% vol. 0.00–21.00% vol.	0.01% vol. 0.01% vol.	... ±4%	... ±0.1% vol.
NO	0–5000 ppm vol. 0–4000 ppm vol.	1 ppm vol. 1 ppm vol.	±4% ±8%	±25 ppm vol. ±50 ppm vol.
λ	0.500–9.999 0.700–1.300	0.001 0.001	... ±4%	... ...

2.1. Methodology

The main measurements conducted during the tests involved engine indication, which entailed recording changes in-cylinder pressure as a function of the crankshaft rotation angle. Additionally, fuel and air consumption were measured, and exhaust emissions, including NOx, HC, CO, CO_2, and soot concentrations, were monitored. The research focused on the co-combustion of hydrogen with diesel fuel and biodiesel (RME). For both cases, the energy share of hydrogen in the total fuel energy supplied to the engine was set at 4%, 7%, 12%, 23%, and 34%. In order to analyze the obtained results, combustion and emission tests were conducted for the engine operating solely on diesel fuel and RME as reference fuels. The tests were carried out under conditions of thermal stabilization with a constant maximum engine load. Engine indication allowed for the analysis of the combustion process, including the determination of key combustion stages such as ignition delay (ID), combustion duration (CD), and the angle of 50% heat release (CA50). Moreover, it facilitated the determination of essential engine operation parameters, including mean indicated pressure (IMEP), thermal efficiency (ITE), and specific energy consumption (SEC). The stability of the dual-fuel engine operation was assessed by analyzing changes in IMEP over 200 consecutive engine cycles.

2.2. Fuels Characteristics

The research involved the use of three fuels: diesel fuel, biodiesel (RME), and hydrogen. Table 4 presents the selected physical and chemical properties of these fuels. Diesel fuel is a typical distillation product of crude oil at atmospheric pressure. It consists of a mixture of naphthenic, paraffinic, and aromatic hydrocarbons, which are components of crude oil. One important parameter of diesel fuel, like any other fuel, is its calorific value, which is 42.7 MJ/kg. Another significant parameter for compression ignition engines is the cetane number, which indicates the fuel's self-ignition capability. Diesel oils commonly available at European petrol stations must meet the EN590 standard and have a cetane number of at least 51.

RME (Rapeseed Methyl Esters) is a biofuel derived from the methyl esters of rapeseed oil fatty acids. It possesses physicochemical properties similar to conventional oil-derived diesel fuel, allowing it to be used as a substitute fuel for compression ignition engines. Biodiesel (RME) is an environmentally friendly fuel that is renewable and biodegradable. Its production from rapeseed oil ensures a CO_2 balance, as part of the emitted carbon dioxide is absorbed during the growth of the oilseed rape used in production. RME has a low sulfur content and excellent lubricating properties, which positively impact engine operation and durability. It is often used as a bio-component in blends with conventional diesel fuel. RME meets the European quality standard EN590 and typically has a higher cetane number than diesel, reaching 56. With about 11% oxygen content, RME enables more efficient combustion and has a slightly lower calorific value than diesel (37.3 MJ/kg).

Table 4. Fuel specifications [25,26].

	Diesel	RME	Hydrogen
Molecular formula	$C_{14}H_{30}$	$CH_3(CH_2)nCOOCH_3$	H_2
Cetane number	51	54	5–10
Octane number	0–15	25	130
Molecular weight (kg/kmol)	170–200	296	2.02
Density at 15 °C (kg/m^3)	840	820–845	0.084
Lower heating value (MJ/kg)	42.7	37.3	119.93
Autoignition temperature (K)	503	534	855
Stoichiometric air-fuel ratio (kg/kg)	14.53	12.3	34.4
Kinematic viscosity at 20 °C (mm^2/s)	4	7.4	-
Flammability limits in air (at%)	0.6–5.5	-	4–75
Ignition energy in air (mJ)	0.24	-	0.02
Diffusion coefficient in air (cm^2/s)	0.038	-	0.61
Oxygen content (wt%)	0	11	0
Hydrogen content (wt%)	15	12	100
Carbon content (wt%)	85	77	0

Hydrogen is recognized as the most abundant element in the universe, albeit usually not in its pure form but rather in various chemical compounds. It is a highly energetic fuel that can be produced without generating carbon emissions. The most common methods for hydrogen production are natural gas steam reforming, coal gasification, and electrolysis. Hydrogen possesses the highest calorific value (approximately 120 MJ/kg) and heat of combustion (based on mass) among all fuels. However, it's very low density presents a disadvantage when considering volume-related values. Hydrogen readily forms flammable and combustible mixtures with air due to its extensive flammability and explosive limits compared to other fuels. In theory, hydrogen boasts numerous advantages as an excellent energy carrier, with water vapor as the byproduct of its combustion. Nevertheless, the production of pure hydrogen is complex and energy-intensive, while its transportation and storage require extraordinary precautions. Due to its high octane number (130), hydrogen is a desirable fuel for spark-ignition engines. However, its low cetane number (5–10) prevents it from being used as a standalone fuel for compression ignition engines.

3. Results

Comparative research was conducted on the co-combustion of hydrogen with diesel fuel and hydrogen with biodiesel-RME in a compression-ignition internal combustion engine. The study focused on examining the effects of hydrogen content on engine efficiency, as well as evaluating the combustion process and exhaust emissions for both liquid fuels.

3.1. Combustion Characteristics

The recorded pressure profile in the cylinder serves as the primary and most reliable source of information for studying the combustion process in a reciprocating engine. The analysis of the indicator diagram, which depicts the heat release rate, is essential for evaluating the engine's performance. Figure 2 provides an overview of the pressure profiles in the cylinder and the heat release for different energy shares of hydrogen compared to the reference profiles obtained with diesel fuel (Figure 2a) and biodiesel (Figure 2b).

In both cases of co-combusting hydrogen with diesel fuel and biodiesel, the maximum pressure values exceeded those of the reference fuels. When hydrogen was co-combusted with diesel fuel, the engine achieved a pressure value of 71 bar for the maximum hydrogen share of 34% at 3 degrees after top dead center (aTDC). Similarly, for the co-combustion of hydrogen with biodiesel, the maximum pressure reached 73 bar at the same hydrogen share and timing. However, the combustion of biodiesel with hydrogen resulted in a more gradual pressure increase, as evidenced by the heat release rate curve.

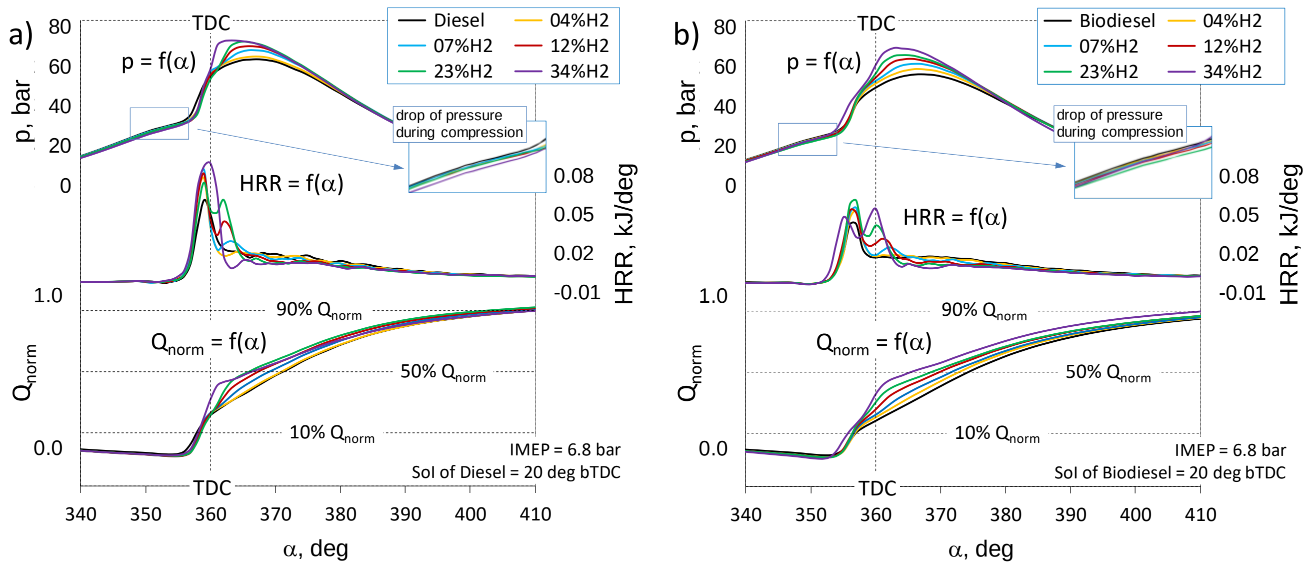

Figure 2. Comparison of the combustion pressure courses and the heat release rate and normalized heat release curves for a dual-fuel engine powered by hydrogen with diesel (**a**) and hydrogen with biodiesel (**b**).

For diesel/hydrogen combustion, hydrogen shares up to 23% led to two local maxima on the heat release rate curve, indicating a two-stage combustion process. At the maximum hydrogen share, the heat release rate curve resembled that of a spark-ignition engine, with the diffusion combustion phase diminishing. The maximum heat release rate value of 89.5 J/deg was recorded at a 34% hydrogen share. In the case of biodiesel/hydrogen combustion, the two-stage combustion occurred for each hydrogen percentage, and the second stage became more pronounced with higher hydrogen shares. The maximum heat release rate value of 61 J/deg was observed at a 23% hydrogen content. Increasing the hydrogen share resulted in a reduction of diffusion phases during combustion.

By integrating and normalizing the heat release rate (HRR) curves, the Q_{norm} curves were derived, providing valuable insights into the combustion process and its stages. These curves were utilized to determine important parameters for engine optimization, including the ignition delay time (ID) at 10% Q_{norm}, combustion duration (CD) at 90% Q_{norm}, and the angle of 50% heat release (CA50) at 50% Q_{norm}.

From the Q_{norm} curves, it is evident that, in both cases, the combustion process undergoes a noticeable change when the hydrogen share reaches 34%, resulting in faster combustion compared to lower hydrogen proportions. This effect is particularly pronounced in the initial phase of the combustion process. Figure 3 illustrates the impact of hydrogen content on the individual combustion phases for both analyzed scenarios.

Examining the influence of hydrogen share on ignition delay, it was observed that only for diesel fuel combustion, a 23% hydrogen share caused a 1-degree increase in ID, while for biodiesel co-combustion, a 34% hydrogen content led to a 2-degree decrease in ID compared to the values obtained with reference fuels.

Significant reductions in combustion duration were observed for both liquid fuels co-combusted with hydrogen. In the case of diesel fuel combustion with hydrogen, the CA90 combustion time decreased to 23% of the hydrogen share, and further increasing the hydrogen percentage to 34% led to a subsequent increase in combustion duration. Notably, for a 34% hydrogen share, a substantial acceleration in combustion rate was observed. However, prior to CA50 and at approximately 40% heat release, the combustion rate slowed down.

For the biodiesel engine, the combustion time was successively shortened as the hydrogen content increased across the entire range. At the maximum hydrogen share, the combustion time was reduced by 13 degrees compared to biodiesel combustion alone.

In both cases, as the hydrogen proportion increased, the CA50 angle shifted closer to the top dead center (TDC). However, it is important to note that during the tests, the injection angle for the liquid fuel remained constant at 20 degrees before top dead center (bTDC).

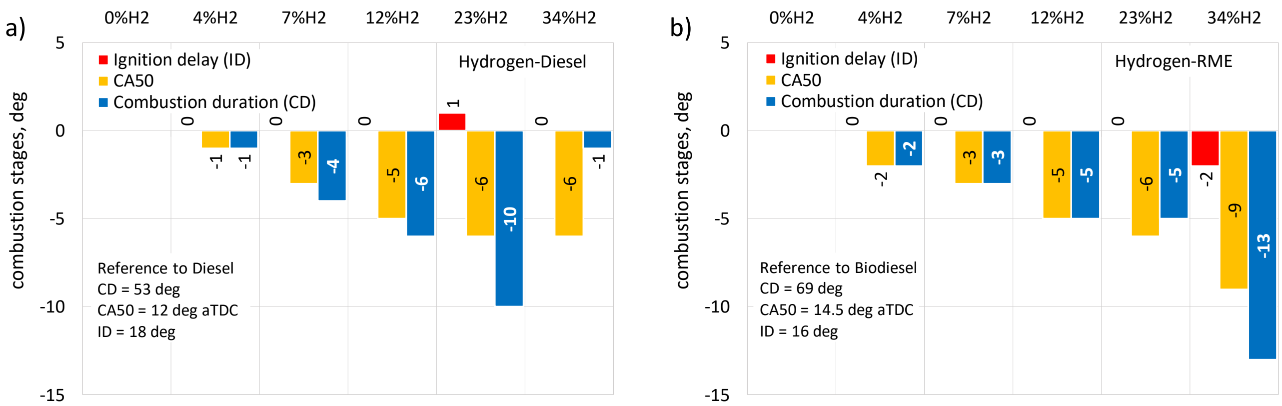

Figure 3. The stages of ignition delay (ID), CA50 and combustion duration (CD) for a dual-fuel engine powered by hydrogen with diesel (**a**) and hydrogen with biodiesel (**b**).

3.2. Performance Characteristics

The utilization of alternative fuels in reciprocating internal combustion engines aims to not only diversify energy sources but also improve their environmental aspects and often enhance engine efficiency. Hydrogen exhibits a high combustion rate, thereby reducing the duration of combustion in a dual-fuel engine. This reduction in combustion duration helps minimize heat loss across system boundaries, resulting in improved thermal efficiency of the engine. Figure 4a illustrates the impact of hydrogen content on engine efficiency for both analyzed cases. It was observed that engine efficiency increased across the entire range of hydrogen content in both cases. Comparing the reference fuels, the engine powered solely by diesel fuel achieved higher efficiency (ITE = 35.1%) than the engine powered by biodiesel (ITE = 32.2%). The optimal efficiency was achieved with a 12% energy share of hydrogen. Notably, the engine fueled by biodiesel experienced a greater efficiency increase for this hydrogen share, with a rise of 7.4%. Further increasing the hydrogen proportion did not yield such a substantial efficiency improvement, although it remained higher than that of the reference fuels. For a 12% hydrogen content in Hydrogen-RME fueling, a greater efficiency increase was achieved compared to diesel fuel, although the absolute value of ITE for diesel fuel was 41%, while for RME, it was 39.6%. For RME fueling, the CA50 angle was 9.5 degrees aTDC, while for diesel fuel, it was 7 degrees aTDC. The differences in these values are also reflected in the ITE values.

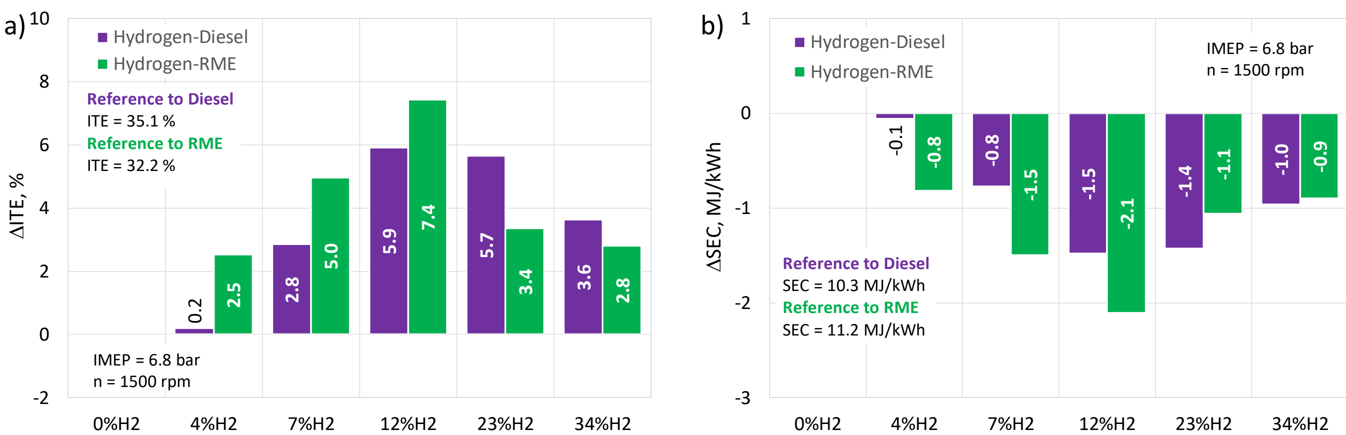

Figure 4. Engine indicated efficiency (ITE) (**a**) and specific energy consumption (SEC) (**b**) for a dual-fuel engine powered by hydrogen with diesel and hydrogen with biodiesel.

Figure 4b illustrates the impact of hydrogen content on the specific energy consumption (SEC) a parameter closely related to ITE. The most significant energy savings, while maintaining the same IMEP value, were achieved with a 12% hydrogen share. In the case of biodiesel, savings of 2.1 MJ/kWh compared to the reference fuel were realized.

An important parameter for evaluating the engine's performance is the consistency of successive engine cycles. The COV_{IMEP} index, which measures the degree of variation in indicated mean effective pressure, is used for this assessment. According to literature [27], the value of this index should not exceed 5%. Figure 5 presents the influence of hydrogen content on the consistency of IMEP values, represented as differences from the values obtained for the reference fuels. For diesel fuel, the COV_{IMEP} value was 1.61%, while for biodiesel, it was slightly higher at 2.6%.

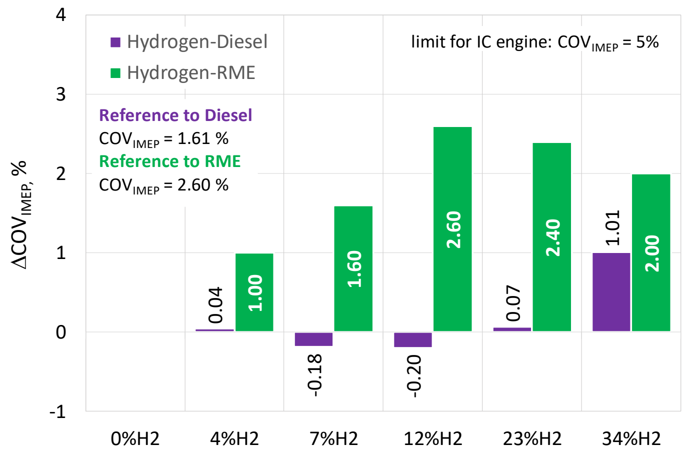

Figure 5. Uniqueness of IMEP (COV_{IMEP}) for a dual-fuel engine powered by hydrogen with diesel and hydrogen with biodiesel.

In the case of hydrogen co-combustion with diesel fuel, only a 34% hydrogen share resulted in a 1% increase in COV_{IMEP}, reaching a value of 2.61%, which is still acceptable. The engine demonstrated high repeatability in subsequent operating cycles. However, a more significant impact on the consistency of engine operation was observed for hydrogen co-combustion with biodiesel. The largest increase in COV_{IMEP} was recorded at a 12% hydrogen share, with a 2.6% increase, resulting in a total COV_{IMEP} value of 5.2%, slightly higher than the permissible value.

In the case of an engine fueled by biodiesel, an increase in the hydrogen content resulted in an increase in COV_{IMEP}, which could be attributed to the change in the combustion process dynamics of biodiesel due to the presence of hydrogen in the fuel-air mixture filling the engine combustion chamber. This led to a shift in the combustion phases compared to the values obtained for the reference fuel. As shown in Figure 6b, when fueled with Hydrogen-RME, there was a significant variation in the crank angle at the end of combustion (CA90), reaching as high as 41 degrees for a 12% hydrogen blend, while for the engine fueled with Hydrogen-Diesel, it was only 12 degrees. The distinctiveness of the RME combustion process with hydrogen compared to diesel fuel is also evident in the heat release rate curves. Due to a constant start of injection angle, the CA50 (Crank Angle at 50% heat release) angle for Hydrogen-Diesel was closer to the optimal value than for Hydrogen-RME fueling, which also contributed to the increase in COV_{IMEP}.

The combustion stages presented in Figure 6 were determined based on average profiles obtained from 200 consecutive engine cycles. Each cycle in a reciprocating engine exhibits some variability, which is reflected in other engine parameters derived from the indication results. Figure 6 displays the dispersion and range of variability for the characteristic combustion stages. The analysis was conducted based on the heat release curves of 200 consecutive engine cycles. To illustrate the matter, two sets of normalized heat release curves (Q_{norm}) are shown for the engine fueled with the reference fuel and a 23% hydrogen share. The analysis reveals that the start of combustion is highly repeatable for both fuels co-combusted with hydrogen. The greatest variation in ignition delay (ID) occurred at a 34% hydrogen share when co-combusted with biodiesel, but it did not exceed 2 degrees of crank angle (CA). Regarding the dispersion of the conventional end of combustion (CD), co-combustion with diesel fuel resulted in a range of 8–13 degrees CA for hydrogen shares up to 23%. Only at a 34% hydrogen share, this dispersion significantly increased to 42 degrees CA. For biodiesel/hydrogen co-combustion, an increase in the uniqueness of the combustion end was observed, reaching a maximum of 53 degrees CA for hydrogen shares up to 23%. However, it slightly decreased at a 34% hydrogen content.

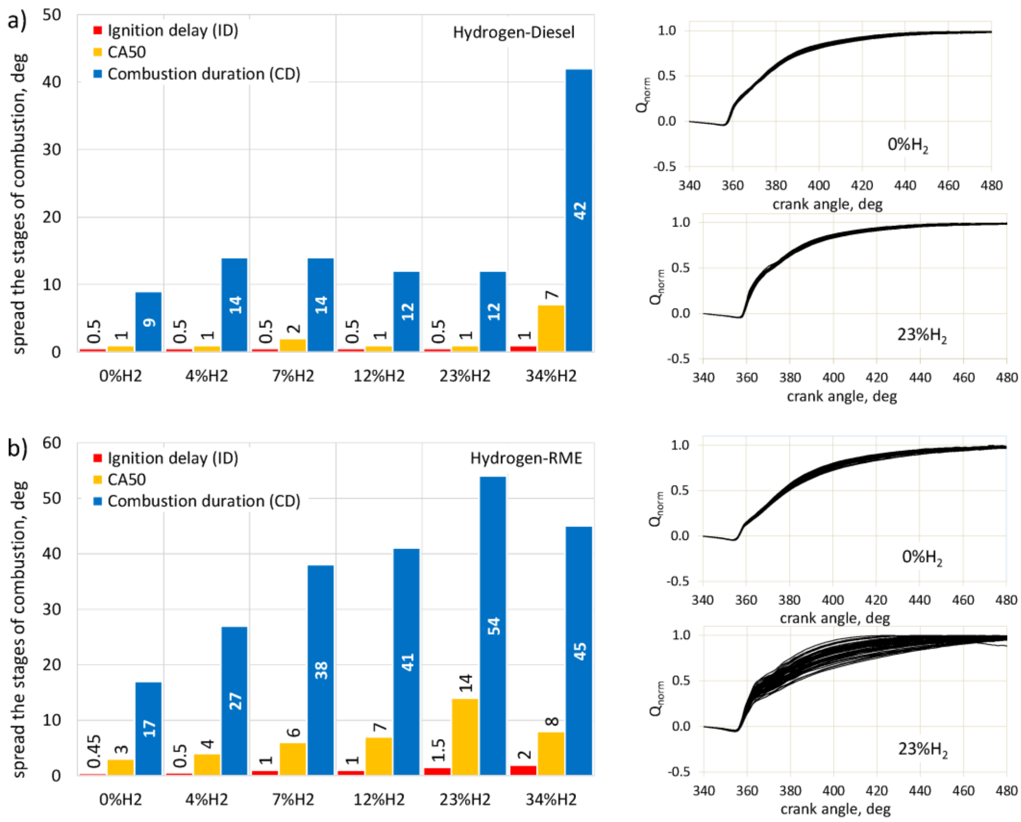

Figure 6. Spread of characteristic combustion stages for hydrogen co-combustion with diesel fuel (**a**) and hydrogen co-combustion with biodiesel (**b**).

The occurrence of the CA angle at 50% heat release for piston engines is typically determined after top dead center (TDC). In this regard, a similar trend to that observed for CD was also noticed. Based on this analysis, it can be concluded that diesel fuel exhibits better compatibility when co-combusted with hydrogen. There is a higher level of reproducibility and stability in the occurrence of the characteristic combustion stages. Hydrogen promotes the increase of combustion rate, shortening the total duration of this process, thus contributing to a significant reduction in heat loss from the combustion chamber.

For a 12% hydrogen content, CA50 was closest to the optimal position for the engine in both cases. This analysis should take into account not only the CA50 angle value itself (Figure 3) but also the variation of this crankshaft angle value's occurrence in consecutive engine cycles.

3.3. Emission Characteristics

The modern energy sector and automotive industry face new challenges that drive the development and improvement of technologies, materials, control systems, and the adoption of low-emission energy sources, including alternative fuels. Hydrogen has emerged as a promising fuel of the future, serving as an alternative to conventional hydrocarbon fossil fuels such as crude oil and natural gas. This gas is highly regarded as an excellent fuel for reciprocating engines due to its high combustion efficiency and negligible emission of harmful and toxic exhaust components. One way to utilize hydrogen in a reciprocating engine is through co-combustion with diesel or biodiesel in a dual-fuel compression-ignition engine. This study presents the exhaust gas emission results from a compression-ignition engine powered by hydrogen, diesel fuel, and a blend of hydrogen and biodiesel (RME), with the gaseous fuel contributing up to 34% of the energy share. The concentrations of NO, HC, CO, CO_2, and soot in the engine's exhaust were analyzed.

Nitrogen oxides. A reciprocating engine, operating by combusting hydrocarbon fuel, often in oxygen-rich conditions, leads to the formation of significant quantities of nitrogen oxides (NOx). Nitrogen oxides are a mixture of various nitrogen compounds with oxygen, produced both within the engine and in its exhaust system. The majority of NOx, approximately 95%, is in the form of nitrogen monoxide (NO), generated under specific conditions during the combustion of the air-fuel mixture within the engine cylinder [26,28]. Optimal conditions for NO formation are present in the high-temperature regions of the combustion chamber, where abundant oxygen and nitrogen are available. Nitrogen oxides are among the most hazardous components present in the exhaust gases of piston engines, including both compression-ignition and spark-ignition engines. Figure 7a illustrates the variations in NO concentration in the engine's exhaust when co-combusting hydrogen with diesel fuel and hydrogen with biodiesel (RME). These changes are compared to the emissions observed with the reference fuels, namely diesel fuel and RME. It is evident that the engine powered solely by biodiesel exhibited lower NO emissions (270 ppm) compared to the engine powered solely by diesel (476 ppm). The addition of hydrogen to both diesel and biodiesel fuels led to an increase in NO emissions from 4% to 34%. Although the concentration gains were higher when hydrogen was burned with biodiesel, the total emissions were higher when hydrogen was burned with diesel. The increased overall emissions associated with the presence of diesel fuel were primarily due to the heightened combustion intensity and higher heat release rate (HRR) during the combustion of the initially prepared mixture in the kinetic phase. Higher HRRs indicate elevated maximum cylinder temperatures, promoting NO formation. The NO concentration measurements were relatively accurate within a range of ±4% of the measured values [29,30].

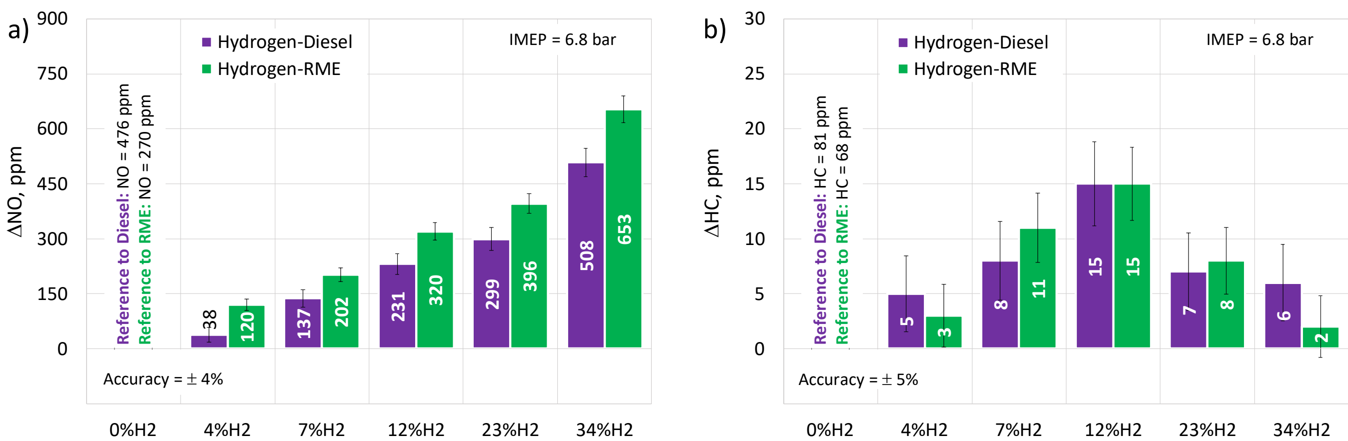

Figure 7. Nitric oxide (NO) (**a**) and hydrocarbons (HC) (**b**) emission for a dual-fuel engine powered by hydrogen with diesel and hydrogen with biodiesel.

Hydrocarbons. Unburned hydrocarbons (HC) are another group of toxic compounds released in the exhaust gases of piston engines. They result from incomplete combustion of the fuel in the engine cylinder and are present in both rich and highly lean mixtures. Excessive HC emissions are primarily caused by low combustion temperatures in lean mixtures, insufficient homogenization of the fuel-air mixture, and the presence of fuel-rich regions, which can be attributed to factors such as fuel injection characteristics. The shape and volume of the combustion chamber, including the size of crevices and cavities where fuel can accumulate with limited access to oxygen, also influence hydrocarbon emissions. Figure 7b illustrates the variations in HC concentration in the exhaust gas from a test engine fueled by hydrogen and diesel fuel, as well as hydrogen and biodiesel, compared to the emissions observed with diesel fuel and biodiesel alone. Upon analyzing the measurement results, it can be observed that the combustion of biodiesel resulted in lower HC emissions (68 ppm) compared to the combustion of diesel fuel (81 ppm). Similarly, the emission increments for hydrogen-biodiesel blends indicate lower total hydrocarbon emissions throughout the entire range of hydrogen content. The highest concentrations of hydrocarbons in the exhaust gas were recorded with a 12% hydrogen content for both tested mixtures. Beyond this concentration, HC emissions decreased due to improved homogeneity of the air-fuel mixture, which can be attributed to a significant increase in the amount of hydrogen supplied to the engine during the intake stroke. The relative accuracy of HC concentration measurements was within ±5% of the measured values [29,30].

Carbon monoxide. Carbon monoxide (CO) is a byproduct of incomplete combustion in reciprocating engines. It is formed in the engine cylinder under conditions of oxygen deficiency in fuel-rich regions and conditions of excess oxygen during the combustion of highly lean mixtures. In compression-ignition engines, where the fuel-air mixture is typically lean, insufficient mixing of fuel with air before ignition leads to inadequate oxidation. This results in the presence of fuel-rich and fuel-lean areas. In the former case, the lack of sufficient oxygen prevents complete oxidation of the carbon present in the fuel. In the latter case, the lower temperature and combustion rate in the lean fuel mixture hinder the complete oxidation of carbon. The carbon content in the hydrocarbon fuel supplied to the engine is a significant factor contributing to excessive CO emissions, which can be mitigated by using alternative fuels like hydrogen. Figure 8a illustrates the CO emissions from a test engine during co-combustion of hydrogen with diesel fuel and hydrogen with RME, compared to emissions measured when using diesel fuel and biodiesel alone. It can be observed that the combustion of biodiesel alone resulted in nearly twice as much CO emissions (1.5%) compared to diesel fuel combustion (0.76%), despite a decrease in the amount of elemental carbon in the cylinder due to the use of biodiesel (Figure 8a) and an increase in active oxygen. The decisive factor in this case was a significant reduction in the combustion intensity of biodiesel, as reflected in a decrease in the heat release rate, which hindered the complete oxidation of carbon. The addition of hydrogen to the reference fuels increased the combustion rate, reduced the amount of carbon in the fuel mixture, and had a positive impact on CO emissions. In both hydrogen-diesel and hydrogen-RME co-combustion, reductions in carbon monoxide concentration in the exhaust gas were observed for all analyzed hydrogen shares. The effect of hydrogen was more pronounced in the co-combustion with biodiesel. The relative accuracy of CO concentration measurements was within ±5% of the measured values [29,30].

Carbon dioxide. Carbon dioxide (CO_2) is a byproduct of complete combustion of hydrocarbon fuel and can indicate the proper progression of combustion in a piston engine cylinder. Although carbon dioxide is not classified as a toxic compound, it has a detrimental impact on the environment as one of the main greenhouse gases that contribute to climate change. High temperatures and an excess of oxygen are prerequisites for the formation of CO_2. Increased consumption of carbon-containing fuels leads to higher carbon dioxide emissions. Therefore, the utilization of alternative fuels such as hydrogen can help reduce CO_2 emissions. Figure 8b illustrates the variations in CO_2 concentration in the exhaust gas of a hydrogen-fueled diesel engine and a hydrogen-biodiesel (RME) engine. Similarly, these changes are compared to the reference fuels. It can be observed that the combustion of diesel fuel alone resulted in a comparable emission of carbon dioxide (7.80%) as the combustion of biodiesel alone (7.89%). The addition and increase of hydrogen content co-combusted with diesel fuel and biodiesel had a positive effect on CO_2 emissions, which was associated with a decrease in the amount of elemental carbon supplied by the fuel (Figure 9a). A more pronounced reduction in CO_2 was observed for RME, which has a lower carbon content compared to diesel fuel. The relative accuracy of CO_2 concentration measurement was within ±5% of the measured values [29,30].

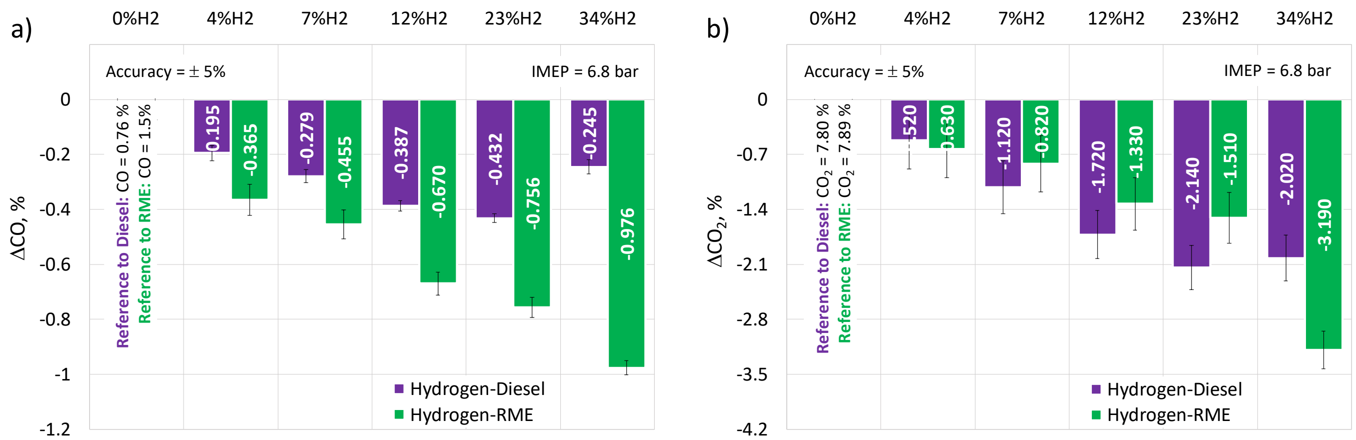

Figure 8. Carbon monoxide (CO) (**a**) and carbon dioxide (CO_2) (**b**) emission for a dual-fuel engine powered by hydrogen with diesel and hydrogen with biodiesel.

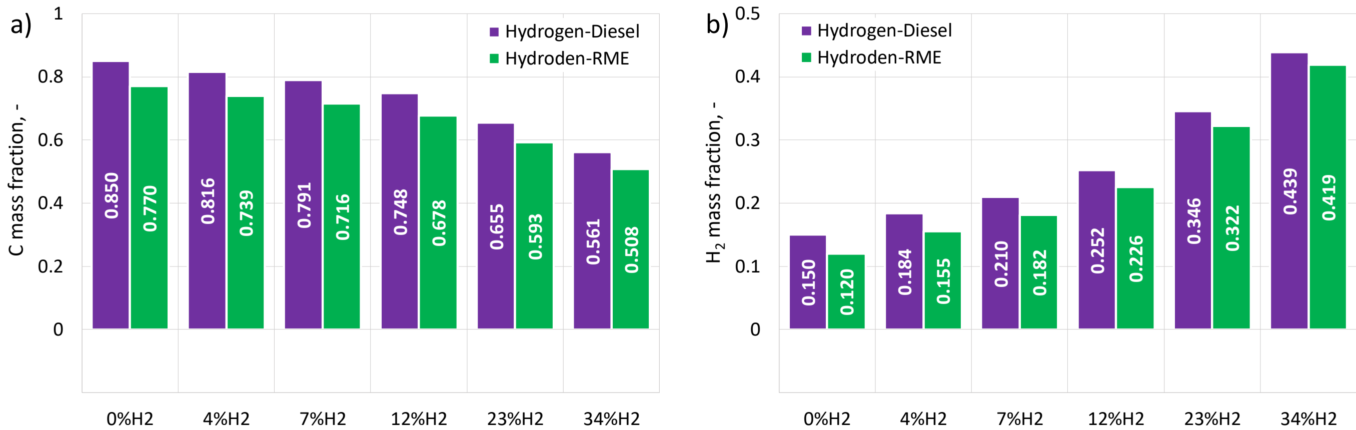

Figure 9. Mass fraction of carbon (**a**) and hydrogen (**b**) in fuel supplied to a dual-fuel engine powered by hydrogen with diesel and hydrogen with biodiesel.

Soot. In a compression-ignition engine, the formation of soot occurs due to the incomplete combustion of carbon-containing fuel, primarily during the diffusion phase, which is influenced by the fuel-air mixture's mixing. Inside the engine cylinder, soot is produced in the form of fine particles consisting of pure carbon. The exhaust system captures heavy hydrocarbons, nitrogen compounds, and sulfur, releasing them into the atmosphere as solid particles (PM). Optimal conditions for soot formation exist in areas of the combustion chamber with high temperatures and fuel-rich regions. Figure 10 illustrates the variations in soot concentration in the engine's exhaust gas when co-combusting hydrogen with diesel fuel and hydrogen from RME, compared to the concentrations obtained for the reference fuels. When considering the reference fuels alone, it is evident that higher soot emissions were associated with the combustion of pure biodiesel (1572 mg/m^3), while the corresponding value for diesel fuel alone was 863 mg/m^3. The higher emissions observed during the combustion of RME can be attributed to the lower heat release rate and the resulting reduced combustion intensity, which leads to fewer carbon particles being oxidized. The impact of hydrogen as a fuel in a compression-ignition engine on soot emissions was found to be positive, both in its co-combustion with diesel fuel and biodiesel. Increasing the amount of hydrogen supplied to the engine during the intake stroke improved the homogeneity of the air-fuel mixture in the cylinder and increased the rate of heat release. Additionally, as the amount of hydrogen increased (Figure 9b), the carbon content decreased (Figure 9a). The beneficial effect of using hydrogen was more pronounced in the case of its co-combustion with biodiesel, where the carbon content was lower compared to diesel-hydrogen combustion. An important factor enabling a greater reduction in soot concentration for hydrogen-RME was the additional oxygen supplied in the biofuel, which facilitated carbon oxidation. The relative accuracy of soot concentration measurement was $\pm$0.05 mg + 3% of the measured value [29,30].

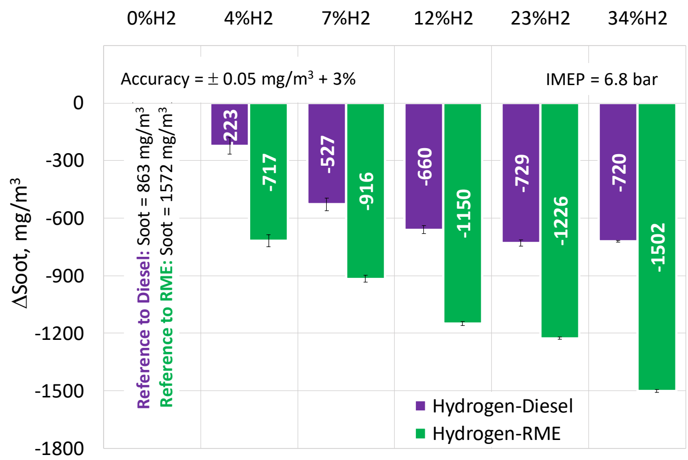

Figure 10. Soot emission for a dual-fuel engine powered by hydrogen with diesel and hydrogen with biodiesel.

4. Conclusions

Research on hydrogen as a fuel for reciprocating internal combustion engines holds significant importance in both the automotive industry and industrial power systems. This importance stems from the need to conserve Earth's natural resources and mitigate air pollution. The presented paper showcases the findings of a compression-ignition engine test involving the co-combustion of hydrogen with diesel fuel and RME biodiesel. Based on the analysis of the test results, the following conclusions can be drawn:

– Biodiesel (RME) co-combusted with hydrogen exhibits a milder combustion process, characterized by smaller pressure and heat release rate increments compared to diesel fuel, a shorter ignition delay and longer combustion duration in comparison to an engine fueled solely by diesel fuel. Both Hydrogen-Diesel and Hydrogen-RME combinations result in the CA50 angle shifting closer to top dead center (TDC) as the hydrogen share increases.
– The highest engine efficiency is achieved with a 12% energy share of hydrogen, but the engine fueled by biodiesel exhibits a more substantial efficiency increase for this hydrogen share.
– An engine powered by biodiesel slightly exhibits poorer work stability, as measured by the COV_{IMEP} value. Hydrogen-RME combustion with a 12% hydrogen share leads to a 2.6% increase in variability.
– Hydrogen demonstrates a positive influence on soot emissions in a compression-ignition engine, both during its co-combustion with diesel fuel and biodiesel. The beneficial effect of using hydrogen is more notable in the Hydrogen-RME configuration.
– Hydrogen demonstrates a positive influence on soot emissions in a compression-ignition engine, both during its co-combustion with diesel fuel and biodiesel. The beneficial effect of using hydrogen is more notable in the Hydrogen-RME con-figuration.

Hydrogen can be efficiently utilized as a fuel in a compression-ignition engine, offering numerous benefits when co-fired with diesel fuel and biodiesel.

Author Contributions: Conceptualization, W.T., A.J. and K.G.-R.; Data curation, W.T. and A.J.; Formal analysis, W.T.; Investigation, W.T., A.J. and K.G.-R.; Methodology, W.T. and A.J.; Writing—original draft, W.T.; Writing—review & editing, W.T. and K.G.-R. All authors have read and agreed to the published version of the manuscript.

Funding: Research was financed by the Ministry of Science and Higher Education of Poland from the funds dedicated to scientific research No. BS/PB 1-100-316/2023/P.

Data Availability Statement: The data used in this study are reported in the paper figures and tables.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Akal, D.; Öztuna, S.; Büyükakın, M.K. A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect. *Int. J. Hydrog. Energy* **2020**, *45*, 35257–35268. [CrossRef]
2. Arbab, M.I.; Masjuki, H.H.; Varman, M.; Kalam, M.A.; Imtenan, S.; Sajjad, H. Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel. *Renew. Sustain. Energy Rev.* **2013**, *22*, 133–147. [CrossRef]
3. Farhan, S.M.; Wang, P. Post-injection strategies for performance improvement and emissions reduction in DI diesel engines—A review. *Fuel Process. Technol.* **2022**, *228*, 107145. [CrossRef]
4. Shinde, B.J.; Karunamurthy, K. Recent progress in hydrogen fuelled internal combustion engine (H2ICE)—A comprehensive outlook. *Mater. Today Proc.* **2022**, *51*, 1568–1579. [CrossRef]
5. Şanlı, A.; Yılmaz, I.T. Cycle-to-cycle combustion analysis in hydrogen fumigated common-rail diesel engine. *Fuel* **2022**, *320*, 123887. [CrossRef]
6. Sharma, P.; Dhar, A. Effect of hydrogen fumigation on combustion stability and unregulated emissions in a diesel fuelled compression ignition engine. *Appl. Energy* **2019**, *253*, 113620. [CrossRef]
7. Zhou, S.; Luo, Z.; Wang, T.; He, M.; Li, R.; Su, B. Research progress on the self-ignition of high-pressure hydrogen discharge: A review. *Int. J. Hydrog. Energy* **2022**, *47*, 9460–9476. [CrossRef]
8. Zhang, K.; Luo, T.; Li, Y.; Zhang, T.; Li, X.; Zhang, Z.; Shang, S.; Zhou, Y.; Zhang, C.; Chen, X.; et al. Effect of ignition, initial pressure and temperature on the lower flammability limit of hydrogen/air mixture. *Int. J. Hydrog. Energy* **2022**, *47*, 15107–15119. [CrossRef]
9. Seelam, N.; Gugulothu, S.K.; Reddy, S.K.; Bhasker, B.; Panda, J.K. Exploration of engine characteristics in a CRDI diesel engine enriched with hydrogen in dual fuel mode using toroidal combustion chamber. *Int. J. Hydrog. Energy* **2022**, *47*, 13157–13167. [CrossRef]
10. Gerpen, J.V. Biodiesel processing and production. *Fuel Process. Technol.* **2005**, *86*, 1097–1107. [CrossRef]
11. Bukkarapu, K.R.; Krishnasamy, A. A critical review on available models to predict engine fuel properties of biodiesel. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111925. [CrossRef]
12. Kanth, S.; Debbarma, S. Comparative performance analysis of diesel engine fuelled with hydrogen enriched edible and non-edible biodiesel. *Int. J. Hydrog. Energy* **2021**, *46*, 10478–10493. [CrossRef]
13. Gomes Antunes, J.M.; Mikalsen, R.; Roskilly, A.P. An experimental study of a direct injection compression ignition hydrogen engine. *Int. J. Hydrog. Energy* **2009**, *34*, 6516–6522. [CrossRef]
14. Liu, X.; Srna, A.; Yip, H.L.; Kook, S.; Chan, Q.N.; Hawkes, E.R. Performance and emissions of hydrogen-diesel dual direct injection (H2DDI) in a single-cylinder compression-ignition engine. *Int. J. Hydrog. Energy* **2021**, *46*, 1302–1314. [CrossRef]
15. Muralidhara, D.M.; Banapurmath, N.R.; Udayaravi, M.; Prabhakar Reddy, C.; Harari, P.A.; Karthik, T. Effect of hydrogen flow rates on the performance of two biodiesels fuelled dual fuel engine. *Mater. Today Proc.* **2022**, *49*, 2189–2196. [CrossRef]
16. Akar, M.A.; Kekilli, E.; Bas, O.; Yildizhan, S.; Serin, H.; Ozcanli, M. Hydrogen enriched waste oil biodiesel usage in compression ignition engine. *Int. J. Hydrog. Energy* **2018**, *43*, 18046–18052. [CrossRef]
17. Köse, H.; Acaroğlu, M. The effect of hydrogen addition to Cynara biodiesel on engine performance and emissions in diesel engine. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**, 1–20. [CrossRef]
18. Tutak, W.; Jamrozik, A.; Grab-Rogaliński, K. Effect of natural gas enrichment with hydrogen on combustion process and emission characteristic of a dual fuel diesel engine. *Int. J. Hydrog. Energy* **2020**, *45*, 9088–9097. [CrossRef]
19. Tuccar, G.; Uludamar, E. Emission and engine performance analysis of a diesel engine using hydrogen enriched pomegranate seed oil biodiesel. *Int. J. Hydrog. Energy* **2018**, *43*, 18014–18019. [CrossRef]
20. Dimitriou, P.; Kumar, M.; Tsujimura, T.; Suzuki, Y. Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine. *Int. J. Hydrog. Energy* **2018**, *43*, 13605–13617. [CrossRef]
21. Köse, H.; Ciniviz, M. An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. *Fuel Process. Technol.* **2013**, *114*, 26–34. [CrossRef]
22. Xia, C.; Brindhadevi, K.; Elfasakhany, A.; Alsehli, M.; Tola, S. Performance, combustion and emission analysis of castor oil biodiesel blends enriched with nanoadditives and hydrogen fuel using CI engine. *Fuel* **2021**, *306*, 121541. [CrossRef]
23. Kanth, S.; Ananad, T.; Debbarma, S.; Das, B. Effect of fuel opening injection pressure and injection timing of hydrogen enriched rice bran biodiesel fuelled in CI engine. *Int. J. Hydrog. Energy* **2021**, *46*, 28789–28800. [CrossRef]

24. Das, S.; Kanth, S.; Das, B.; Debbarma, S. Experimental evaluation of hydrogen enrichment in a dual-fueled CRDI diesel engine. *Int. J. Hydrog. Energy* **2022**, *47*, 11039–11051. [CrossRef]
25. Stępień, Z.A. Comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges. *Energies* **2021**, *14*, 6504. [CrossRef]
26. Hosseini, S.E.; Butler, B. An overview of development and challenges in hydrogen powered vehicles. *Int. J. Green Energy* **2020**, *17*, 13–37. [CrossRef]
27. Heywood, J.B. *Internal Combustion Engine Fundamentals*, 2nd ed.; McGraw-Hill Education: New York, NY, USA, 2018.
28. Clapp, L.J.; Jenkin, M.E. Analysis of the relationship between ambient levels of O_3, NO_2 and NO as a function of NOx in the UK. *Atmos. Environ.* **2001**, *35*, 6391–6405. [CrossRef]
29. Jamrozik, A.; Tutak, W.; Grab-Rogaliński, K. An experimental study on the performance and emission of the diesel/CNG dual-fuel combustion mode in a stationary CI engine. *Energies* **2019**, *12*, 3857. [CrossRef]
30. Tutak, W.; Jamrozik, A.; Grab-Rogaliński, K. The effect of RME-1-butanol blends on combustion, performance and emission of a direct injection diesel engine. *Energies* **2021**, *14*, 2941. [CrossRef]