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EFFECT OF 20 % HYDROGEN ENRICHMENT IN SPARK-IGNITION INTERNAL COMBUSTION ENGINE USING STOCK IGNITION SETTINGS

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Abstract

This study presents the experimental results of a spark-ignition internal combustion engine modified for dual-fuel operation with hydrogen and gasoline. The primary objective was to investigate the effects of hydrogen enrichment, specifically a 20% hydrogen energy share on the combustion characteristics under standard ignition timing. Using high-resolution in-cylinder pressure measurements, we evaluated key combustion parameters including combustion duration, heat release rate, and mass fraction burned (MFB) profiles. The findings demonstrate a significant acceleration of the combustion process with hydrogen addition, evidenced by a marked reduction in combustion duration and an earlier occurrence of the MFB50 point. Importantly, the original ignition timing settings, optimized for pure gasoline operation, were retained throughout the tests to isolate the impact of hydrogen on flame development. The results provide critical insight into the dynamic interaction between hydrogen enrichment and conventional engine calibration, with implications for engine efficiency, emissions, and the feasibility of low-intrusion dual-fuel retrofitting.

1 Introduction

The transition toward sustainable energy systems has restored interest in alternative fuels for internal combustion engines (ICEs). Hydrogen, owing to its high reactivity, wide flammability range, and carbon-free nature, has emerged as a promising energy carrier for reducing emissions and improving combustion efficiency. In compression ignition (CI) engines, numerous studies have established the viability of hydrogen as a supplementary fuel, with dual-fuel operation yielding benefits such as extended lean-burn capability, lower particulate matter formation, and increased thermal efficiency [1][2].

Experimental investigations in hydrogen–diesel dual-fuel configurations reveal that hydrogen addition leads to shorter combustion durations and more complete fuel oxidization, enhancing overall engine performance under various operating conditions [3]. These effects are particularly pronounced when hydrogen is introduced in precise ratios alongside diesel, as documented in studies that analyze engine operation across a range of hydrogen energy shares [4][5]. Moreover, recent work has expanded this analysis to include advanced mixing techniques, alternative chamber geometries, and emissions performance [6][7].

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Despite these encouraging results in CI engines, similar advancements in spark-ignition (SI) platforms are less mature. Although hydrogen–gasoline dual-fuel SI engines have received increasing attention in recent years, the majority of studies have focused on scenarios involving direct hydrogen injection or adjusted spark timing strategies optimized specifically for hydrogen-enriched operation [8][9]. There remains a notable lack of empirical data on systems utilizing intake port hydrogen injection operated under factory-calibrated gasoline ignition timing, an important configuration for practical retrofitting of legacy engine platforms.

This gap is significant, as intake port injection is among the most cost-effective and non-invasive methods of hydrogen integration. Its adoption in existing engines could enable rapid deployment of low-carbon technologies without necessitating full redesigns or complex engine control recalibrations. Studies such as those by Gopal et al. [6] and Vavra et al. [7] suggest that even modest hydrogen additions can yield combustion efficiency improvements in ICEs using simple port-injection methods.

2 Materials and Methods

2.1 Materials

2.1.1 Engine and Overhaul Procedure

The experimental and simulation studies were conducted using a BMW M43B18 spark-ignition internal combustion engine, selected for its well-documented architecture, robust operational record, and broad support in both physical testing and numerical modeling environments. To ensure consistent, high-fidelity measurement results, the engine underwent a complete mechanical overhaul prior to the commencement of testing. The reconditioning process involved a full teardown and inspection of all major engine components. In the cylinder head, valve guides and valves were replaced, valve seats were re-cut, and the head mating face was resurfaced. Each cylinder bore in the engine block was re-honed, and the deck surface was machined to ensure flatness. All piston rings, main and connecting rod bearings, as well as sealing gaskets, were replaced with new, standard components. Ancillary mechanical parts were cleaned, visually inspected, and either reused if within specification or replaced as necessary. Following reassembly, the engine underwent a break-in procedure according to MAHLE's recommended protocol [10]. This gradual run-in phase was critical to allow mechanical components to properly bed-in under thermally and dynamically realistic load conditions. The procedure consisted of staged operation across increasing loads and speeds, thereby ensuring stabilized engine behavior prior to experimental testing. The core technical specifications of the engine remained unmodified throughout the study and are summarized in Table 1. These unchanged parameters ensured that the observed combustion behavior under dual-fuel operation could be attributed solely to fuel composition changes and not to hardware alterations.

Table 1. Base engine data

Parameter	Value
Engine Code	M43B18
Engine Type	Four-stroke, inline-4
Bore	84 [mm]
Displacement	1796 [cm³]
Valvetrain	8 valves (2/cylinder)
Fuel System	Port fuel injection
Compression Ratio	9,7:1
Fuel Pressure	3,5 [bar]

2.1.2Engine control unit and wiring

A fully programmable standalone engine control unit (ECU) was integrated into the system using a custom-built wiring harness. This setup provided comprehensive control over all essential engine parameters, including fuel injection timing and ignition advance, enabling real-time monitoring and accurate adjustments during operation.

The selected ECU featured wideband lambda sensor compatibility and a robust real-time fuel and ignition mapping interface, both of which were crucial for maintaining optimal combustion under dual-fuel conditions. The custom wiring harness ensured accurate data transmission between sensors, actuators, and the control unit, thus facilitating stable engine operation and reliable data collection throughout the testing cycle.

2.1.3Combustion analyzer

Combustion data were collected using a high-fidelity diagnostic system from BDN Automotive, centered around the CA-6 six-channel combustion analyzer. This system is designed for time-synchronized in-cylinder pressure measurement, providing high-resolution data critical for understanding thermodynamic processes and calibrating simulation models.

A pressure transducer (AVL GH01D) was installed via an AVL spark plug with integrated measurement capability, paired with an AVL AT6356E 4-chanell amplifier. The analyzer operated at a sampling rate of 1 MHz, allowing crank-angle-resolved analysis of peak pressure, pressure rise rate, and mass fraction burned. Synchronization was achieved using a 60-2 crankshaft trigger wheel, which provided accurate crank-angle referencing and ensured all combustion data were phase-aligned with the engine cycle.

Table 2. Combustion analysis system specifications

Component	Specification
Pressure transducer	AVL GH01D
Amplifier	AVL AT6356E
Sensitivity	5,3 [pC/bar]
Linearity Error	±0.3%
Natural Frequency	170 [kHz]
Sampling Rate	1 [MHz]
Operating Range	0–300 [bar]
Synchronization	60-2 crank trigger wheel

2.1.4Fuels

The engine was fueled with commercially available 95-octane gasoline and high-purity hydrogen. The gasoline, conforming to Euro 95 specifications, was selected for its wide availability and knock resistance. Hydrogen was supplied from certified high-pressure cylinders and regulated to ensure precise and consistent delivery.

Both fuels were subjected to rigorous handling protocols. Gasoline was stored in sealed, temperature-controlled containers to avoid vapor loss and density variation. Prior to testing, fuel temperature was regulated to 20 °C. Hydrogen was introduced through an electronically controlled port injection system, calibrated to deliver the desired energy content while maintaining combustion stability.

2.1.5 Environmental Conditions

To minimize external influence and ensure repeatability, ambient testing conditions were tightly regulated. Intake air pressure, ambient temperature, and fuel temperatures were continuously monitored using AVL and PressureTech sensors. The test cell environment was stabilized prior to each measurement cycle. Environmental conditions maintained during the tests can be found in Table 3.

Table 3. Environmental Conditions

Parameter	Value
Air pressure	998 [hPa]
Ambient temperature	19 [°C]
Fuel temperature	20 [°C]
Gasoline pressure	3,5 [bar]
Hydrogen pressure	5 [bar]

2.1.6 Hydrogen Supply and Safety System

Hydrogen was introduced via port injection using injectors positioned 50 mm upstream of the intake valves. The injection system was synchronized with the ECU for precise delivery according to the target energy equivalence ratios.

The hydrogen supply system included a mass flow meter, pressure regulator, and high-pressure storage tank. Safety was ensured through gas leak detectors, mechanical relief valves, certified high-pressure tubing, and emergency shutdown protocols. All safety measures were implemented in accordance with current standards for laboratory hydrogen combustion systems.

2.2 Methods

2.2.1Engine dyno test with gasoline and hydrogen in dual-fuel operation

The dual-fuel validation experiments were carried out using a blend of hydrogen and gasoline, with hydrogen contributing 20% of the total energy input. The engine was operated across a speed range of 1500 to 3500 RPM under wide-open throttle (WOT) conditions. The primary goal was to evaluate the impact of hydrogen enrichment on combustion behavior, power output, and thermodynamic characteristics.

Table 4. Energy share and lambda value under dual-fuel operation

RPM	Used hydrogen	Used gasoline	Lambda value
1500 [1/min]	85 [l/min]	4,87 [kg/h]	0,99 [-]
2000 [1/min]	119 [l/min]	6,79 [kg/h]	0,98 [-]
2500 [1/min]	145 [l/min]	8,22 [kg/h]	1,02 [-]
3000 [1/min]	165 [l/min]	12,36 [kg/h]	1,01 [-]
3500 [1/min]	195 [l/min]	14,69 [kg/h]	0,99 [-]

A stoichiometric air–fuel ratio ($\lambda = 1$) was maintained by adjusting the gasoline injector pulse width while precisely metering the hydrogen using a calibrated flow control system. Spark timing was set near the Maximum Brake Torque (MBT) point but constrained below the knock limit to ensure stable operation.

Key parameters included engine speed, torque, brake power, air mass flow, exhaust gas temperature (EGT), and the individual consumption of both fuels were recorded in the ECU and PUMA log files. The AVL testbed platform ensured consistent environmental and engine control. Gasoline flow was measured using AVL 735S, AVL 752C, and AVL 7531.21 systems that also control fuel temperature hence density. Hydrogen delivery was precisely controlled and monitored by hydrogen reductor and a hydrogen mass flow sensor. For hydrogen gas pressure reduction, we used a Messer FE53 hydrogen pressure regulator. For the hydrogen mass measurement we used a Sensortech S418 hydrogen mass meter. Intake air was stabilized through AVL Airsonix systems, while output torque and power were recorded using the AVL DynoRoad 200 dynamometer.

Table 5. Environmental Conditions

Parameter	Value	Description
Engine speed	1500, 2000, 2500, 3000, 3500 [RPM]	Mid-load operating range
Load	100 [%]	Full load for consistent pressure conditions
Hydrogen energy share	20 [%]	To evaluate hydrogen enrichment effect
Spark Timing	-	Same as under gasoline operation
Equivalence Ratio	1 [λ]	Stoichiometric for comparability

2.2.2 Combustion Analysis

The combustion behavior was thoroughly analyzed using high-resolution in-cylinder pressure data acquired under steady-state conditions at multiple operating points. Data were collected over a minimum of 100 consecutive cycles per test point to allow for cycle-averaged analysis and to minimize the influence of transient anomalies or cycle-to-cycle variations.

Combustion metrics were derived using the Rassweiler–Withrow method, a widely accepted approach for analyzing pressure traces in spark-ignition engines. The main parameters evaluated were:

- Mass Fraction Burned (MFB) Profiles: Key combustion phasing points, namely MFB10, MFB50, and MFB90, were calculated to determine the progression of the combustion event. These points represent 10%, 50%, and 90% of the total energy release, respectively, and provide insight into ignition delay, rapid combustion phase, and combustion completion.
- Combustion Duration: Two metrics were used to quantify combustion duration: (1) the total combustion duration from the start of combustion (SOC) to the end of combustion (EOC), and (2) the interval between MFB10 and MFB90. The SOC–EOC method captures the entire combustion process, including ignition delay and residual burning, whereas the MFB90–MFB10 method emphasizes the main combustion phase and is less sensitive to minor anomalies.
- Rate of Heat Release (ROHR): Derived from the pressure and volume data using a first-law thermodynamics approach. ROHR analysis was used to assess the intensity and shape of the combustion event. This parameter also helped in identifying abnormal combustion phenomena such as knock or pre-ignition.
- Peak In-Cylinder Pressure and Pressure Rise Rate: These parameters were monitored to evaluate the potential for knock and the overall aggressiveness of combustion. Higher peak pressures and rapid pressure rise rates are indicative of more intense combustion, which may require re-optimization of spark timing or other control strategies.

Special attention was given to the influence of hydrogen enrichment on combustion phasing. With a 20% hydrogen energy share, the MFB50 consistently shifted closer to top dead center (TDC), indicating a faster flame propagation speed. Combustion duration, particularly the MFB90–MFB10 interval, was reduced across all tested RPM ranges, demonstrating the high reactivity and fast burning nature of hydrogen.

3 Results

The experimental results revealed a significant alteration in combustion dynamics when transitioning from pure gasoline to hydrogen-enriched dual-fuel operation. At a hydrogen energy share of 20%, and with the spark timing settings preserved at values optimized for gasoline-only operation, combustion events exhibited a marked acceleration across all tested engine speeds. A consistent shift in MFB50 toward top dead center (TDC) was observed in the dual-fuel mode, reflecting earlier and more rapid energy release. This phasing advancement, paired with the reduction in combustion duration (as defined by MFB90–MFB10), indicates that the combustion process becomes more concentrated and completes faster with hydrogen addition. These effects were especially pronounced at lower and mid-range engine speeds, where combustion stability and ignition delay are typically more sensitive to fuel properties.

While this acceleration in flame development contributes to improved combustion efficiency, it also introduces challenges related to spark timing optimization. Under the fixed ignition timing strategy used in this study—optimized for maximum brake torque (MBT) during gasoline operation—the advanced combustion phasing in the dual-fuel mode leads to peak pressure occurring earlier in the cycle. This phenomenon may result in increased mechanical stress and thermal loading, potentially affecting engine durability and efficiency.

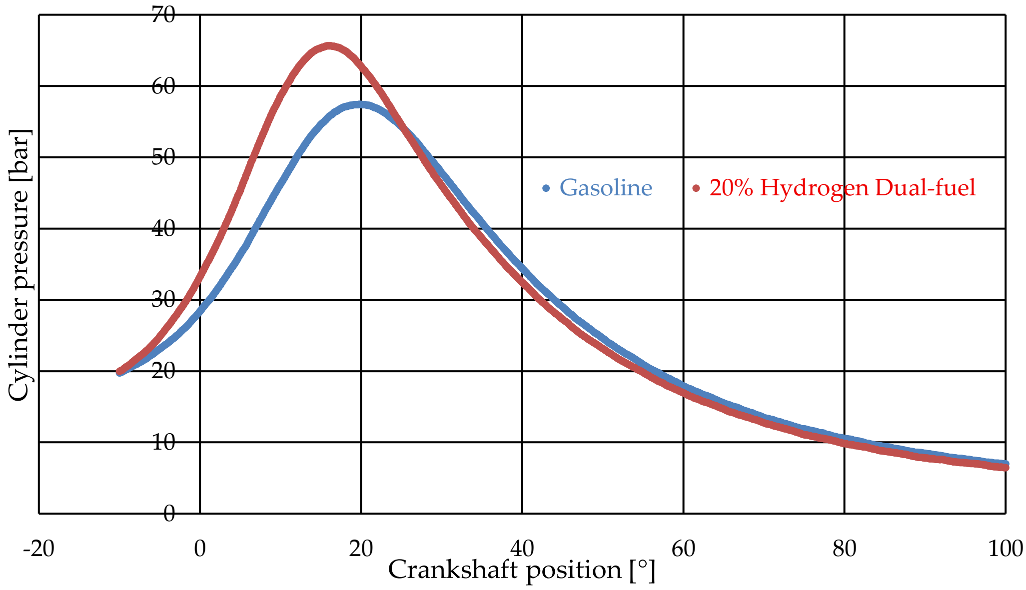

Figure 1. Cylinder pressure on 1500RPM

Figure 1 illustrates the in-cylinder pressure trace at 1500 RPM for both baseline gasoline and 20% hydrogen dual-fuel operation, with the ignition timing fixed at the value optimized for pure gasoline. The comparison clearly reveals that in dual-fuel mode, the combustion initiates more rapidly, as evidenced by the steeper pressure rise immediately after top dead center (TDC). This indicates a significantly more dynamic flame development when hydrogen is introduced.

Moreover, the pressure peak occurs earlier and reaches a higher maximum value compared to gasoline-only operation. This shift implies that hydrogen enrichment leads to both an acceleration of the combustion process and an increase in peak cylinder pressure. These effects, while beneficial in terms of burn efficiency, also suggest the necessity for ignition timing recalibration in dual-fuel operation to prevent excessive mechanical loading and optimize performance.

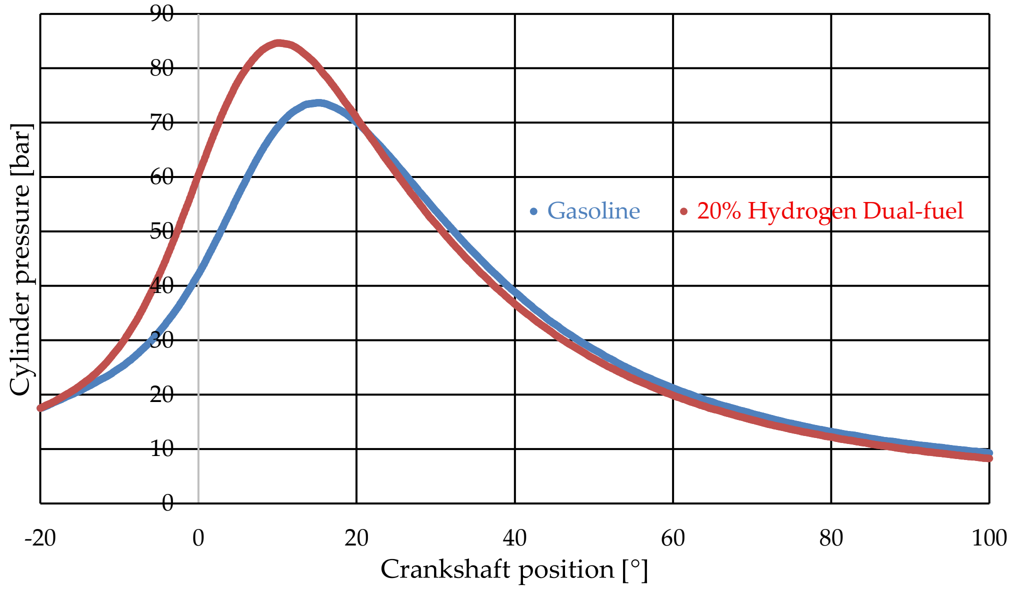

Figure 2. Cylinder pressure on 3000 RPM

Figure 2 presents the cylinder pressure traces at 3000 RPM for both gasoline-only and 20% hydrogen dual-fuel operation under identical ignition timing optimized for pure gasoline. Similar to the trend observed at 1500 RPM, the combustion in dual-fuel mode initiates earlier and progresses more rapidly. This accelerated flame development results in a pronounced forward shift in the pressure rise, leading to an earlier and more intense peak in cylinder pressure.

The increase in maximum in-cylinder pressure under dual-fuel conditions confirms that the hydrogen-enriched mixture burns significantly faster even at higher engine speeds. As a consequence, the retained gasoline-specific ignition advance becomes increasingly unfavorable, causing the combustion to complete prematurely relative to the ideal phasing of the crank shaft for mechanical and thermal efficiency. This further reinforces the need for spark timing recalibration to ensure optimal pressure development and engine durability across the entire operational range.

4 Conclusions

This study presents a detailed investigation of combustion characteristics in a spark-ignition engine operating under hydrogen–gasoline dual-fuel conditions, with a fixed ignition timing strategy initially optimized for gasoline. The introduction of hydrogen containing 20% of all the energy provided resulted in a noticeable acceleration of the combustion process, evidenced by reduced combustion duration and an advancement of the MFB50 point toward top dead center.

These findings highlight hydrogen's potential to improve combustion efficiency due to its high reactivity and fast flame speed. However, they also demonstrate the limitations of retaining gasoline-optimized ignition settings in dual-fuel operation. Without ignition timing recalibration, the earlier peak pressure and shortened burn period may lead to adverse engine performance and increased mechanical stress.

Therefore, this study concludes that successful implementation of hydrogen enrichment in spark-ignition engines requires not only hardware adaptation for fuel delivery but also control system optimization, particularly regarding spark timing. Future work should focus on real-time adaptive ignition control strategies, knock mitigation, and performance mapping under varying hydrogen shares to fully exploit the advantages of hydrogen dual-fuel combustion.

The results provide a solid foundation for further research into sustainable engine operation and offer practical insights for retrofitting existing engine platforms with low-carbon fuel solutions.

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