COMPARATIVE PERFORMANCE STUDY OF A MODIFIED GASOLINE ENGINE WITH THROTTLE-VALVE-DRIVEN MECHANICAL HYDROGEN INJECTOR

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Abstract

In this study, a single-cylinder, air-cooled, 4-stroke, spark-ignited internal combustion engine was modified to operate with both gasoline and gas-phase hydrogen. The engine cylinder cover was redesigned, and an enhanced mechanical hydrogen injector was attached to it. Measurement devices capable of capturing all critical test parameters for comparison purposes were integrated into the test engine. Additionally, all necessary safety equipment was adapted to ensure the safe delivery of hydrogen to the engine. The engine was initially tested with gasoline, and values for engine torque, brake power, specific fuel consumption, TE, and VE were recorded at air throttle openings of 20º to 90º in 10º increments and speeds ranging from 1000 to 3900 rpm. The same parameters were then measured using gas-phase hydrogen. In the experiments conducted with gasoline, optimal performance was achieved at air throttle openings of 60º to 90º and engine speeds of 2350 to 3400 rpm. In the experiments using hydrogen, the most favorable values were observed between 1300 and 1775 rpm at a 30º air throttle opening. When comparing the performance of gasoline and hydrogen in the same engine, results indicated that using gaseous hydrogen led to a 79.54% reduction in engine power and a 73.44% decrease in engine torque. This reduction is considered typical, given that the lower calorific value of hydrogen in the gas phase, at the same pressure and temperature (1 bar, 20 ºC), is approximately 0.010 MJ/l, compared to around 34 MJ/l for gasoline. During testing, issues such as knocking, pre-ignition, and backfire typically associated with intake manifold injection did not occur. No prior studies have employed a direct hydrogen injection method into the combustion chamber with a mechanically activated Hydrogen Injector driven by the intake valve.

1. INTRODUCTION

Hydrogen-fueled engines are attractive due to their lower exhaust emissions compared to fossil-fuel internal combustion engines. Hydrogen offers advantages in Spark Ignition (SI) engines because of its low ignition temperature, wide flammability range in fuel/air mixtures, and high combustion speed. It is considered a clean fuel, producing no Carbon Dioxide (CO_2), Unburned Hydrocarbons (UHC), and generating lower Nitrogen oxide (NO_x) emissions. However, pre-mixing hydrogen with intake air before feeding it into the combustion chamber can cause backfiring and knocking [1]. Engine output power is limited by the low calorific value per unit volume of gaseous hydrogen, especially at low pressures [2]. Additionally, as hydrogen does not naturally exist as a molecular element, its production is costly, requiring extraction from various sources through different methods [3]. The total carbon emissions from hydrogen production also make Life Cycle Analysis (LCA) critically important depending on production methods [4]. Hydrogen production from renewable energy sources is significant in terms of emissions reduction [5],[6],[7]. One major obstacle to widespread hydrogen use as a fuel is its high

production cost, which can range from 1.4 to 8.4 USD/kg when including carbon capture processes [8]. Another significant challenge in replacing fossil-fueled vehicles with hydrogen-fueled vehicles lies in hydrogen storage systems, which require high safety standards, substantial energy for storage, and lightweight yet high-capacity tanks. Current technologies allow for only about 19.4% of a storage tank's weight to be hydrogen [9]. Fossil-fueled Internal Combustion Engines (ICE) produce Carbon Monoxide (CO), NO_x, UHC, Particulate Matter (PM), and Greenhouse Gases (GHG) as combustion products [10]. Compared to gasoline engines, Hydrogen-fueled Internal Combustion Engines (H_2ICE) operate more efficiently with lean mixtures due to hydrogen's high energy content. Hydrogen also has a higher flame speed, lower ignition energy (0.02 MJ), and a higher ignition temperature than other fuels [11]. Due to its high diffusivity, low ignition energy, and high flame speed relative to gasoline and methane, hydrogen is well-suited for SI engines [12]. Hydrogen use in SI engines can take several forms: injection into the intake manifold, cold hydrogen injection directly into the combustion chamber, or use in combination with gasoline and other fuels [8]. Hydrogen can also be used in Compression Ignition (CI) engines, where different injector types are employed to introduce high-pressure hydrogen into the cylinder [13]. Thus, in CI engines, injector design is as critical as engine structure [14]. Hydrogen use in CI engines has been shown to reduce CO_2, CO, HC, and smoke levels by over 50% under optimal conditions. Another approach involves using liquid hydrogen, which requires minimal modification to conventional ICEs. In this system, liquefied hydrogen is converted to cold hydrogen gas in an expansion chamber before injection into the combustion chamber. Cold hydrogen injection reduces NO_x emissions and prevents pre-ignition [15],[16].

2. MATERIALS AND METHODS

In this study, a single-cylinder, air-cooled gasoline engine was modified to operate with both gasoline and gaseous fuels. Various measuring devices and sensors were installed on the engine to monitor and record experimental data. The hydrogen gas used in the experiments was supplied in 150-bar pressure tubes, with a pressure-regulating device attached to ensure consistent pressure during testing. Pressure gauges (Figure 1, A-B) display both the gas pressure within the tube and the regulated pressure supplied to the engine. A flow meter connected to the pressure regulator allows measurement of the gas flow rate fed to the engine. To prevent hazards from backfiring in the combustion chamber, a water safety system was installed after the flow meter. Both gasoline and hydrogen gas were tested as fuels in the same engine, with comparisons made between engine performance and efficiency for each fuel type. Intake air to the engine was measured using a tank-orifice setup (Figure 1). For gasoline testing, Specific Fuel Consumption (SFC) was measured with a scaled glass tube and a 3-way valve connected to the fuel line (Figure 1, B-F). A water brake mechanism and torque meter, linked to the engine crankshaft, were used to measure engine brake power and torque, while engine speed was monitored via a tachometer connected to the same system. To prevent overheating, deformation, or jamming of the hydrogen injector, its body was cooled with externally supplied mains water. Additionally, the temperatures of the engine oil and exhaust gases were monitored with separate thermometers (Figure 1, U). Figure 1 provides a detailed schematic of the experimental setup. To address premature ignition issues with hydrogen, as noted in the literature, a novel solution was developed. In this approach, the engine cylinder head was redesigned, and a specialized injector was added to directly inject hydrogen into the combustion chamber [17].

A: Gasoline reservoir
B: Scale tube (Gasoline)
C: Orifice (Air Intake)
D: Inclined manometer (Air)
E: Air tank
F: 3-way valve (Gasoline)
G: Gasoline supply to ICE
H: Air Intake to ICE
I: Cooling water out
J: Gas injector
K: Water inlet
L: Pressure gauge (exhaust gases)
M: Brake device water in
N: Tachometer and torquemeter
O: Water outlet
P: Air cooled ICE
Q: Brake
R: Carburator
S: Manometer
T: Multipurpose measurement device
U: Temperature controller (Oil)

Figure 1. Schematic view of the experimental setup

In this study, a single-cylinder internal combustion, 4-stroke, air-cooled gasoline engine (Table 1) was modified and the compression ratio was increased from 1/7 to 1/8. A specially designed mechanical injector that would directly inject hydrogen in the gas phase into the combustion chamber was connected to the cylinder head of the engine (Figure 2). The technical specifications of the engine used in the experiments are given in Table 1.

Table 1. The technical specifications of the test engine

Specification	Unit
Producer Name and Model	Briggs Stratton, 1972 (USA)
Number of the Piston	1
Piston Diameter and Stroke (mm)	66.45- 66.68
Compression Rate	1/8
Power (Kw)	3 (3000 rpm)
Engine Speed (rpm)	1000-4500
Cooling	Air
Valve Type	L
Ignition Type	SI
Stroke Number	4

A: Single cylinder ICE
B: Top View of ICE without cylinder head
C: Cylinder head with Injector
D: Cylinder head, injector and the gasket
E: Bottom view of cylinder Head
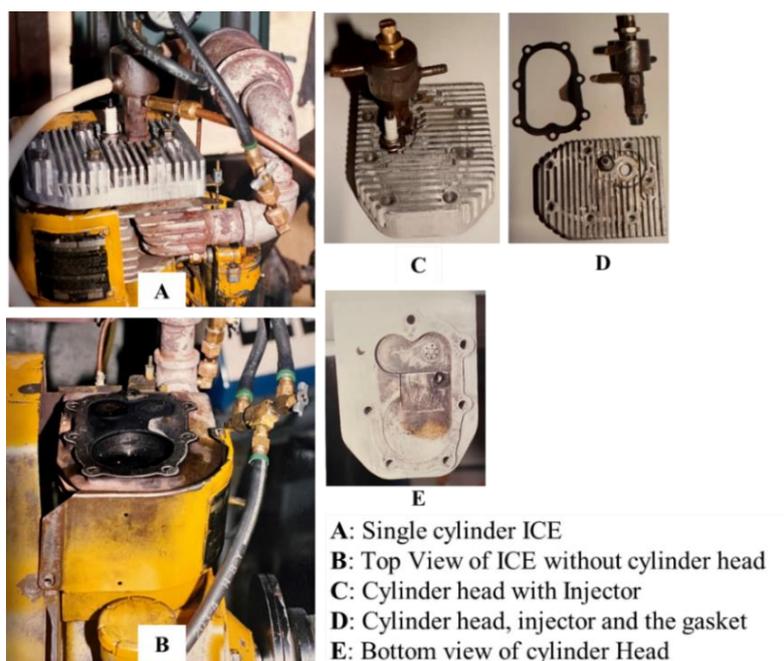
Figure 2. Single piston ICE, cylinder head, ınjector, and the gasket

The injector is mounted on the engine cylinder head and driven by the intake valve (Figure 2). The injector's timing for intake valve opening can be adjusted by modifying its connection height to the cylinder head (Figure 3, H-K). A pressure spring (Figure 3, I) closes the injector, and the spring pressure can be fine-tuned to completely seal the hydrogen path (Figure 3, J). To ensure complete closure of the gas path, the valve in the injector (Figure 3, A) blocks both the hydrogen inlet (Figure 3, D) and the gas flow channels (Figure 3, C). A water jacket (Figure 3, G) surrounds the upper part of the injector to prevent blockage due to engine heat. By adjusting the injector's height concerning the intake valve, the timing of hydrogen injection can be optimized, thereby eliminating early ignition issues noted in the literature through testing different height settings.

A: Injector Valve
B: Gas Injection Holes
C: Gas Feeding
D: Hydrogen Inlet
E: Cooling Water In
F: Cooling Water Out
G: Cooling Jacket
H: Adjusting Bolt
I: Spring
J: Spring Force Adjusting Screw
K: Connection to Cylinder Head

(a)   **(b)**
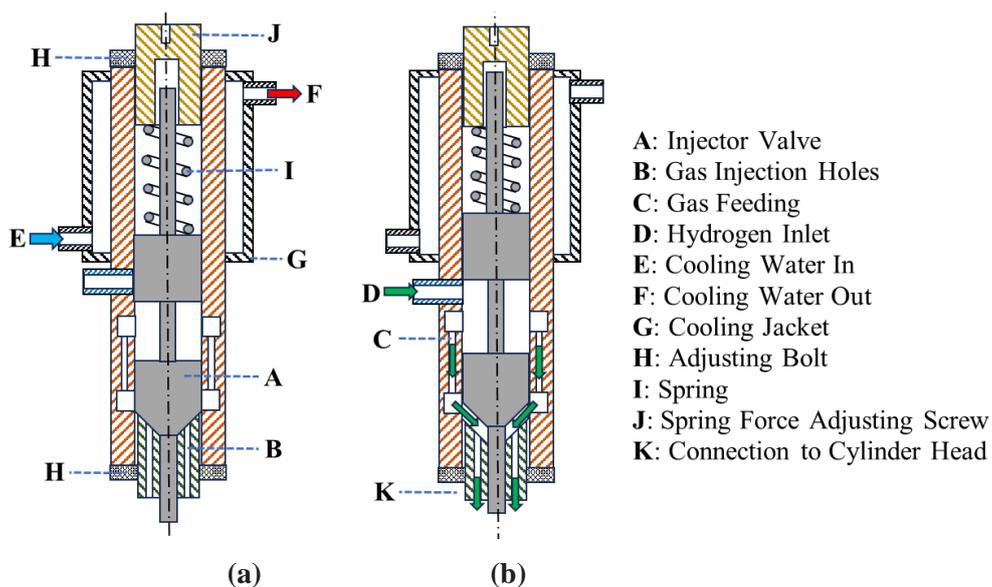
Figure 3. Hydrogen injector and working principle (a: Closed, b: Open)

A mechanically actuated hydrogen injector (MAHI) was designed and implemented for direct hydrogen injection into the combustion chamber. The closed (Figure 3, a) and open (Figure 3, b) positions of the injector are shown schematically in Figure 3. The injector is driven by the intake valve (Figure 4, B); it opens when the intake valve opens (Figure 4, b) and closes when the intake valve closes, aided by the spring mechanism (Figure 4, a).

(a)   **(b)**

A: Hydrogen Injector   D: Piston
B: Intake Valve   E: Hydrogen Feeding
C: Cylinder Head   F: Spark Plug
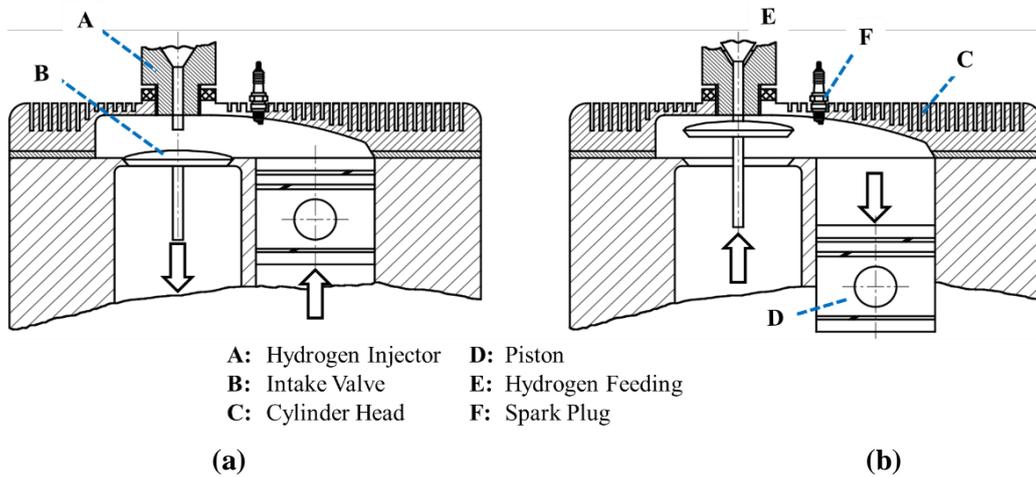
Figure 4. The cross-section of the combustion chamber and injection principle.

The final design and main components of the hydrogen injector, shown in Figure 3 as a technical drawing, are presented in Figure 5. The injector consists of five main parts: the body, which attaches to the cylinder head (Figure 5, D); the injector valve, which opens and closes the hydrogen flow path (Figure 5, A); the spring, which keeps the valve in the closed position (Figure 5, I); the screw for adjusting the spring pressure (Figure 5, J); and the nipple that facilitates hydrogen entry (Figure 5, D).

A: Injector Valve
D: Hydrogen Inlet
E: Cooling Water In
F: Cooling Water Out
G: Cooling Jacket
I: Spring
J: Spring Force Adjusting Screw
K: Connection to Cylinder Head
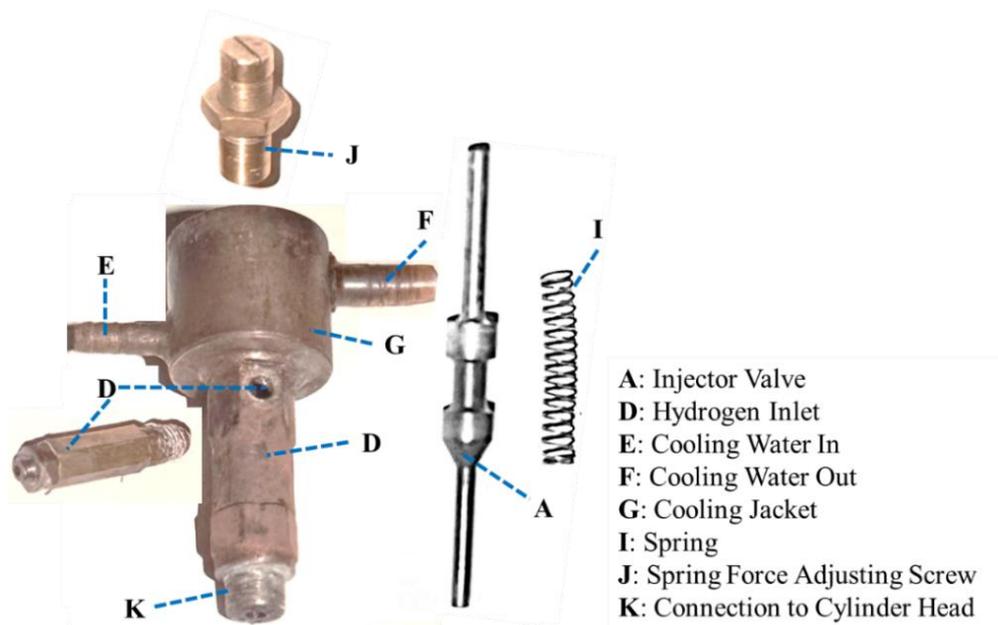
Figure 5. Mechanically Activated Hydrogen Injector and main parts

The modified engine was first tested with gasoline, and all experimental data were recorded. During testing, the combustion air throttle angle was adjustable from 20º to 90º in 10º increments. The fuel

quantity entering the engine was varied at each throttle angle, and the engine was tested at speeds ranging from 1000 to 4100 rpm. For each combination of throttle angle and engine speed, data on brake torque, brake power, specific fuel consumption, combustion airflow, exhaust gas temperature, and engine oil temperature were continuously recorded. Each experimental condition was repeated three times, and the average values were tabulated. Using the experimental data, engine TE and VE were also calculated. The recorded and calculated data were then compared to assess the engine's performance when operating with gasoline versus hydrogen.

3. RESULTS AND DISCUSSION

3.1. Experimental Analysis and Results of GICE

To establish a baseline with gasoline for the modified engine, experiments were conducted at throttle openings of 30º-90º and engine speeds between 2000 and 3900 rpm, with all experimental data recorded. Key parameters such as brake torque, combustion airflow rate, and fuel flow rate were measured at various throttle angles and engine speeds using torque and speed measurement devices connected to the engine crankshaft (Figure 1, Q-N). Additional data, including exhaust gas temperature and engine oil temperature, were also recorded. Based on the collected data, performance metrics such as engine brake power, TE, VE, SFC, and excess air coefficient were calculated. In Figure 6, from left to right, the power curves for torque values obtained at engine speeds of 1300-3500 rpm for throttle openings of 30º, 40º, 50º, 60º, 70º, 80º, and 90º are shown.
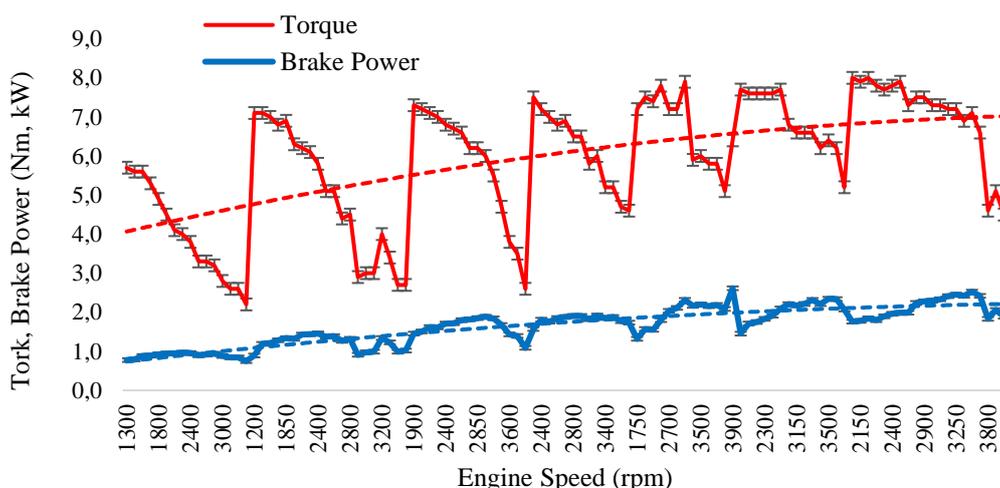
Figure 6. GICE Engine speed, torque, and Brake power

In Figure 6, the peaks in the curves from left to right correspond to the degree of throttle opening (30-90º). The summary table derived from the data tables (Table 2, lines 1, 3, 5, 6, 7) indicates that the engine achieves optimal torque performance at throttle openings of 60º, 80º, and 90º, within the speed range of 2350-2600 rpm.

Table 2. Optimum performance variables of GICE

Test No	Throttle Angle (°)	Engine Speed (rpm)	Torque (Nm)	Brake Power (kW)	SFC (gr/kW)	VE (%)	TE (%)
1	80	2600	7.7	2.10	376.0	22.0	42.8
2	80	3400	6.2	2.21	391.1	21.1	43.3
3	60	2400	7.2	1.81	318.8	25.7	43.6
4	90	3500	6.6	2.42	425.1	19.4	43.7
5	90	3400	7.1	2.53	434.8	19.0	44.6
6	90	2350	7.7	1.89	309.9	21.1	47.0
7	60	2400	7.0	1.76	264.3	31.3	51.1

It was found that TE also reaches high values at the optimum engine torque. The region marked in green in the graph in Figure 6 represents the range where both engine torque and power are at their optimum. The SFC data for the engine operating with gasoline, measured at air throttle openings of 30-90º (9 angles) and engine speeds from 1200 to 3900 rpm, are presented in Figure 7. The graph highlights the experimental conditions where the highest engine torque and the lowest fuel consumption occur. It was determined that the operating conditions that yield optimum engine torque also correspond to the lowest specific fuel consumption, as shown in Figure 7.
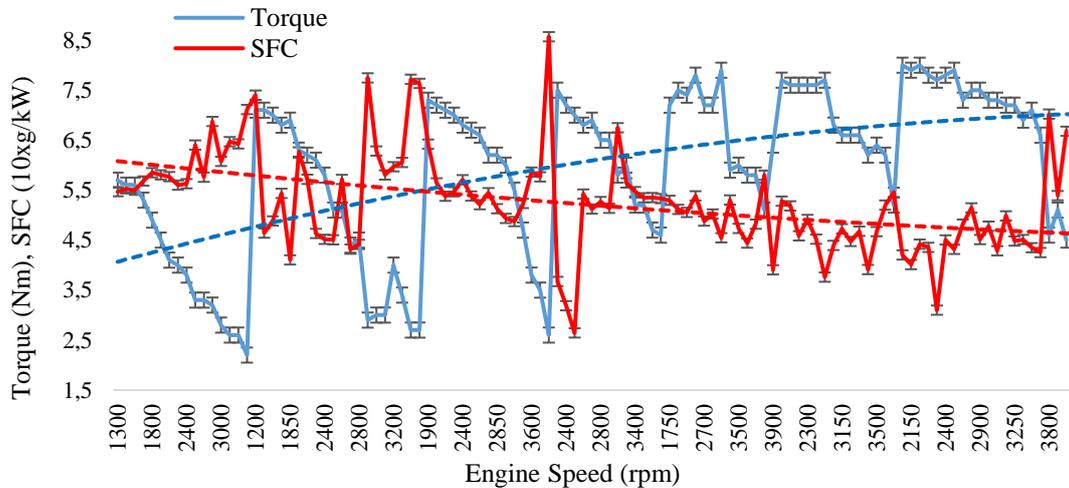
Figure 7. GICE Engine speed, torque, SFC

TE and VE values, calculated using fuel consumption, fuel lower heating value, and engine air flow data, are presented in Figure 8. Based on the data summarized in Figure 8 and Table 2, the optimum operating conditions for the engine running on gasoline are found at air throttle openings of 60º, 80º, and 90º, and within the speed range of 2350-2600 rpm. The engine's TE was determined to range from 42.8% to 51.1%, while its VE ranged from 21.1% to 31.3% (Table 2).
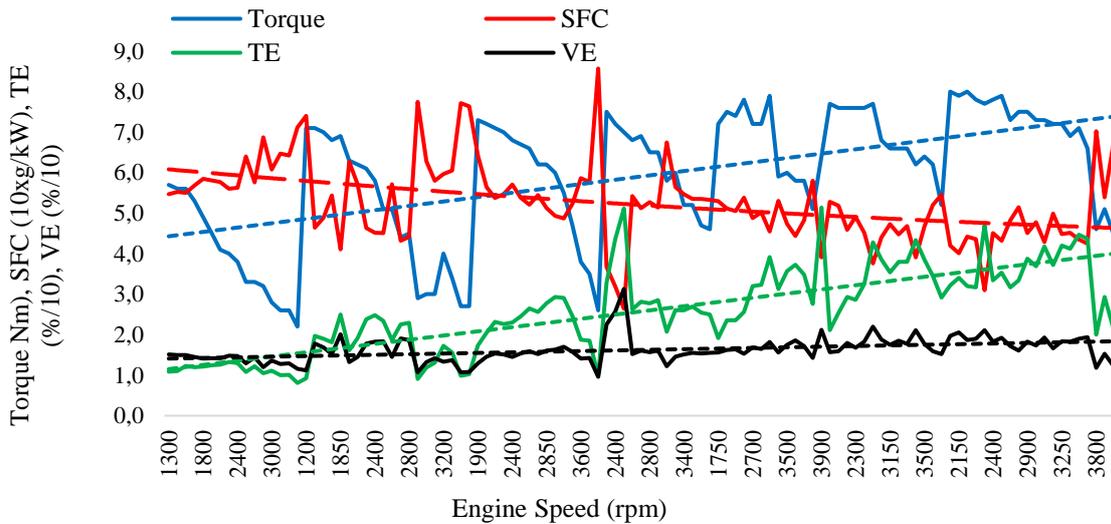
Figure 8. GICE Engine speed, Torque, SFC, TE, VE

In the experiments conducted with gasoline, the most optimal operating conditions were found at air throttle openings of 60º to 90º and engine speeds between 2350 and 3400 rpm. The highest torque of 6.4 Nm was achieved at 90º throttle opening and 3900 rpm, with a brake power of 2.61 kW and a SFC of 390.5 g/kWh. The highest brake power of 1.76 kW was observed at 70º throttle opening and 2100 rpm, with a torque of 8 Nm and an SFC of 420.3 g/kWh. The highest TE of 51.4% was recorded at 70º throttle opening and 3900 rpm, with a torque of 6.4 Nm and a brake power of 2.61 kW. The highest VE of 31.3% was achieved at 60º throttle opening and 2400 rpm, with a torque of 7 Nm, brake power of 1.76 kW, and a TE of 51.1%.

3.2. Experimental Analysis and Results of H₂ICE

After the experiments with the modified gasoline engine, which was redesigned to accommodate the hydrogen injector, additional tests were conducted using the direct injection method into the combustion chamber with the specially developed injector (Figure 5). To facilitate comparisons with the gasoline engine, data on engine torque, brake power, specific fuel consumption, TE, and VE were considered. The specially designed mechanical injector (Figure 5) was created to inject hydrogen directly into the combustion chamber. Hydrogen, supplied from a cylinder at 150 bar pressure, was reduced to 0.25 bar by a pressure regulator before being fed into the engine. This pressure was maintained constant throughout the experiments. The injector, which is normally in the closed position due to the spring pressure (Figure 4, a), is mechanically opened by the intake valve (Figure 4, b), and hydrogen at 0.25 bar is injected into the combustion chamber using the suction effect of the piston (Figure 4, b).
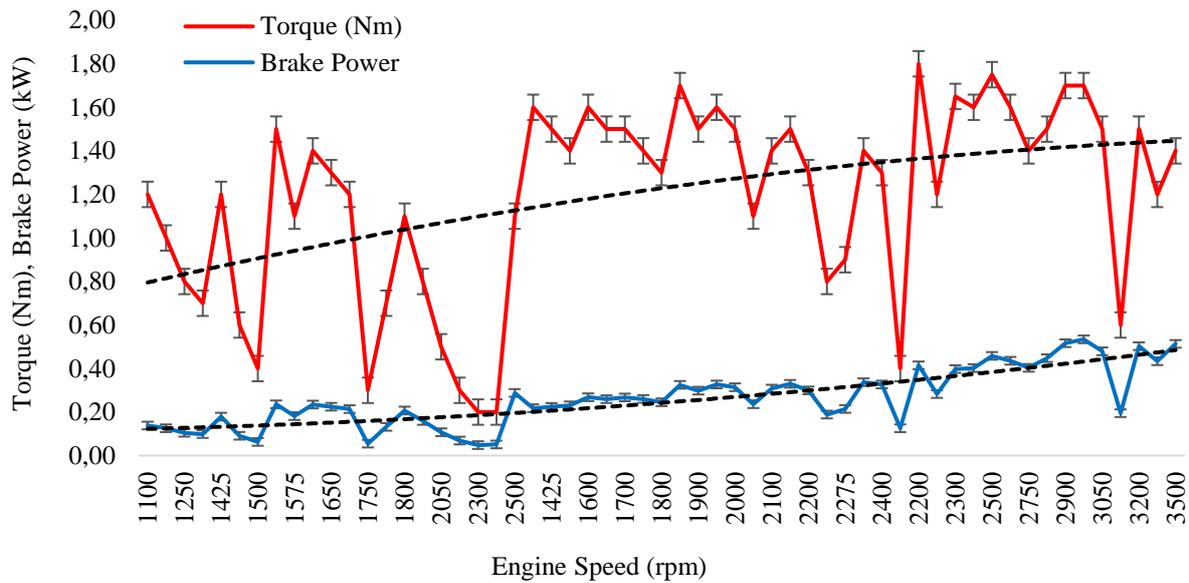
Figure 9. H$_2$ICE Engine speed; Torque, Brake power

In the experiments conducted with hydrogen, Figure 9 shows that the engine produces the highest torque in the range of 2300-2850 rpm at air throttle openings of 20º and 30º, and the highest brake power between 2850-3200 rpm. However, experiments at air throttle openings above 40º were not studied, as the engine exhibited low performance under these conditions. The cause of this was determined to be the insufficient amount of hydrogen fed into the combustion chamber in the gas phase at throttle openings above 40º.
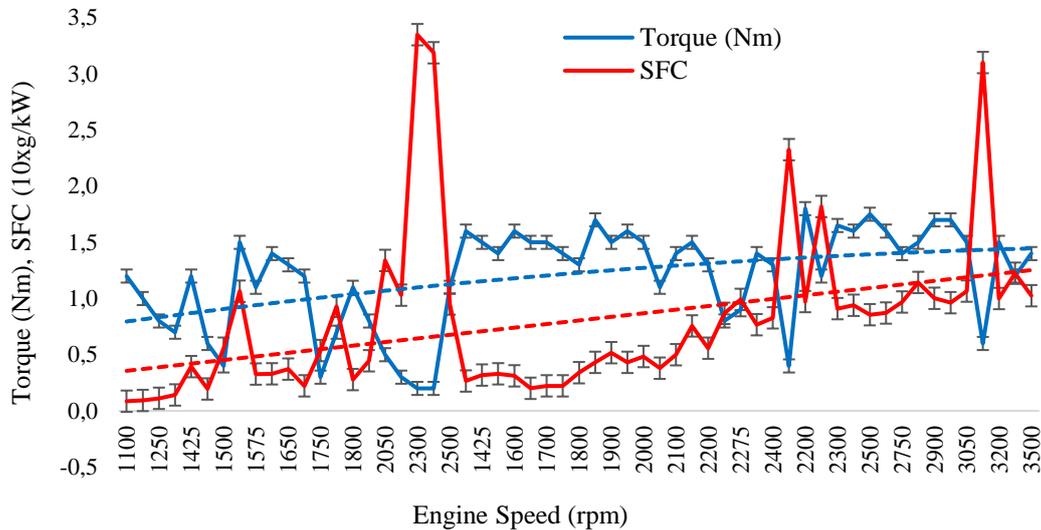
Figure 10. H$_2$ICE Engine speed, torque, SFC

As shown in the summary data in Table 3, the lowest SFC values, in contrast to the maximum torque and power values of the engine, occur in the range of 1350-1800 rpm. The optimum operating conditions are observed at 1300-1775 rpm with 20º and 30º air throttle angles.

Table 3. Optimum performance variables of H$_2$ICE

Test No	Throttle Angle (°)	Engine Speed (rpm)	Torque (Nm)	Brake Power (kW)	SFC (kg/kW)	TE (%)	VE (%)
1	30	1425	1.50	0.224	0.319	9.40	53.07
2	30	1600	1.60	0.268	0.312	9.59	52.23
3	30	1300	1.60	0.218	0.266	11.28	54.05
4	30	1775	1.40	0.260	0.223	13.43	44.71
5	30	1700	1.50	0.267	0.223	13.43	48.06
6	30	1650	1.50	0.259	0.201	14.92	48.81

The VE and TE data obtained by operating the modified engine with hydrogen are given in Figure 11. It is seen from the graphs given in Figure 11 that the optimum operating range of VE and TE occurs in the range of 20 and 30º air throttle angle at 1300-1800 rpm engine speed.
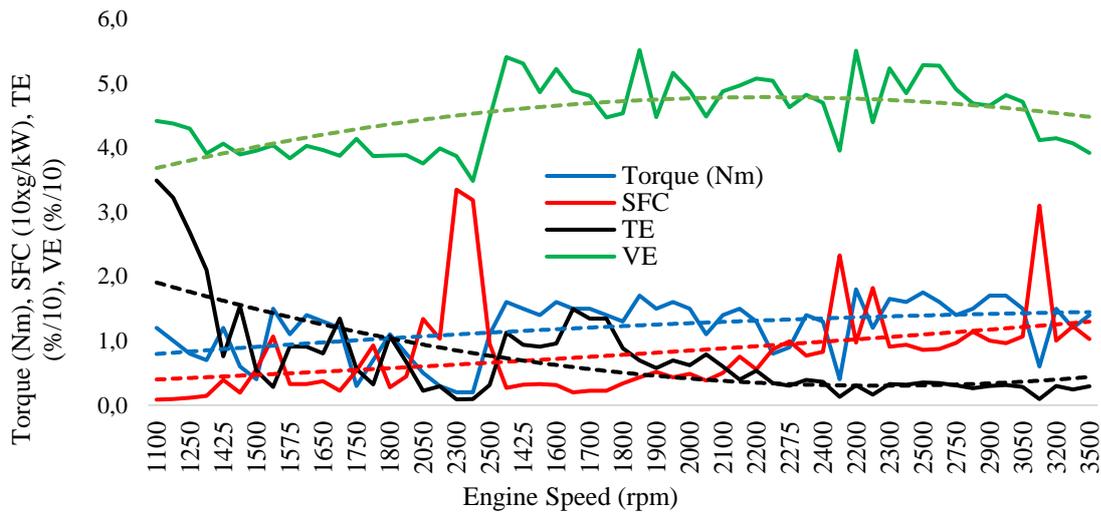
Figure 11. H$_2$ICE Engine speed, torque, SFC, TE, VE

Table 3 shows that under optimum conditions, the VE ranges from 44.71% to 54.05%, while the TE varies between 9.4% and 14.92%. The TE decreases inversely with the increase in VE. This is because the hydrogen/air mixture in the gas phase is limited by an upper bound. In other words, assuming ideal combustion conditions for the engine (piston diameter: 66.45 mm, stroke: 66.68 mm), a theoretical power calculation was made for the 1800 rpm experimental condition (Table 4, line 3). Under hydrogen/air mixture conditions (2 moles H$_2$, 1 mole O$_2$), the theoretical power was calculated to be 0.1473 kW. Given that the measured power for this experimental condition was 0.207 kW, it is evident that the mixture is being supercharged into the combustion chamber. The experimental data corresponding to this theoretical power value is 0.207 kW, as shown in Table 4, line 3. Considering the combustion efficiency, it can be concluded that the engine is operating with rich mixtures and is supercharged. Therefore, the TE is low, while the VE is high.

Table 4. Optimum performance variables of H_2ICE

Test No	Throttle Angle (°)	Engine Speed (rpm)	Torque (Nm)	Brake Power (kW)	SFC (kg/kW)	TE (%)	VE (%)
1	30	1425	1.50	0.224	0.319	9.40	53.07
2	30	1600	1.60	0.268	0.312	9.59	52.23
3	20	1800	1.10	0.207	0.279	10.74	38.78
4	30	1300	1.60	0.218	0.266	11.28	54.05
5	20	1700	1.20	0.214	0.223	13.43	38.72
6	30	1775	1.40	0.260	0.223	13.43	44.71
7	30	1700	1.50	0.267	0.223	13.43	48.06
8	30	1650	1.50	0.259	0.201	14.92	48.81

In the experiments conducted with hydrogen, the most optimal values were achieved in the range of 1300-1775 rpm with a 30° air throttle opening. The highest brake power of 0.534 kW was measured at 40°, 3000 rpm, with 1.7 Nm torque, 0.414 kW brake power, and a SFC of 0.93. TE was found to be 34.91% at 20°, 1100 rpm, with 1.2 Nm torque and 0.138 kW brake power. At 30°, 1825 rpm, with 1.7 Nm torque and 0.325 kW brake power, TE was 6.94%, while VE was 55.16%. A summary of the comparison of the key parameters is presented in Table 5.

3.3. Comparative Performance Analysis of GICE and H_2ICE

The important performance data obtained as a result of operating the engine with gasoline and hydrogen were compared. The data obtained by using the mechanical injector driven by the intake valve, specific to the engine used in the experiment, are summarized in Table 5. Compared to gasoline, hydrogen's Engine Torque was 25.56%, and Engine Brake Power was 20.46%. TE was 67.92%, and VE was 176%.

Table 5. Comparisons of critical engine parameters.

Specifications	Unit	GICE	H_2ICE	%
Torque	Nm	6.4	1.7	26.56
Brake Power	kW	2.61	0.534	20.46
SFC	g/kW	390.5	0.93	
TE	%	51.4	34.91	67.92
VE	%	31.3	55.16	176.2

There have been several studies and applications exploring hydrogen mixing with air before feeding it into the intake manifold and directly injecting it into the combustion chamber at various pressures [18],[19],[20]. However, no studies have utilized MAHI driven by the intake valve, as used in this experimental research. Some studies have explored hydrogen gas compression chambers to increase the hydrogen pressure fed to the intake air, thereby boosting engine power in pressure-augmented H_2ICE systems. Additionally, hybrid systems employing both intake manifold and combustion chamber direct injection methods have been proposed to reduce exhaust emissions and enhance engine efficiency [21]. Another study compared gasoline and hydrogen in spark SI engines with timed injections into the intake manifold via electronic control units. This study observed a 19.06% decrease in power but a 3.16% improvement in thermal brake efficiency, along with reduced NO_x emissions at higher engine speeds

[22]. Further research has investigated Laser Ignition (LI) systems for hydrogen-air mixtures, showing that LI engines outperform traditional SI systems. It was reported that hydrogen-fueled engines convert fuel energy into useful work at a 35.74% higher rate than gasoline engines [23],[24]. Another study found that due to the lower calorific value of the hydrogen/air mixture, theoretical engine power was 14% lower, but there was a 95% reduction in NO_x emissions, and 45% brake thermal power could be achieved [25]. These results align with the findings of this study. Hydrogen-fueled engines in transportation systems have been reported to operate at 20-25% efficiency compared to fossil-fueled vehicles, offering advantages such as high energy conversion efficiency, low noise, and zero exhaust emissions, although challenges in storage and infrastructure remain [15] Another study recommended direct injection into the combustion chamber to achieve 45% TE and lower exhaust emissions, stating that this method prevents issues like knocking, pre-ignition, and backfire, which are common in intake manifold injection. However, it also identified technical problems such as high oil consumption and hydrogen leakage into the crankcase during combustion chamber injection [26]. A numerical analysis of the H_2/diesel fuel mixture in compression ignition engines showed that varying hydrogen doses (0.05% to 50% by volume), engine speed (1000-4000 rpm), and air/fuel ratios (10-80%) improved engine performance and reduced emissions [27].

4. CONCLUSION

Experiments were conducted on a modified single-cylinder, 4-stroke, air-cooled spark-ignition (SI) internal combustion engine (ICE) using both gasoline and hydrogen as fuels. The tests were carried out at air throttle angles ranging from 20º to 90º and engine speeds between 1000 and 3900 rpm. When comparing the performance of gasoline and hydrogen on the same engine, it was found that the use of gaseous hydrogen resulted in a significant loss of engine power (79.54%) and torque (73.44%). This reduction is attributed to the lower calorific value of hydrogen in its gaseous phase, which is approximately 0.010 MJ/l at 1 bar and 20ºC, compared to gasoline's calorific value of around 34 MJ/l [28]. During the tests, issues such as knocking, pre-combustion, and backfire commonly encountered when hydrogen is injected into the intake manifold were not observed. Based on these findings, it seems unlikely to achieve the same torque and power with gaseous hydrogen unless the hydrogen pressure is increased within the same cylinder volume. An alternative solution could be to increase the cylinder volume. In these experiments, hydrogen was injected into the combustion chamber at a pressure of 0.25 bar for safety reasons; however, testing with higher hydrogen pressures could provide additional insights.

NOMENCLATURE

ICE: Internal Combustion Engine
CI: Compression Ignition
SI: Spark Ignition
LI: Laser Ignition
UHC: Unburned Hydrocarbons
PM: Particle Materials
GICE: Gasoline-fueled Fueled Internal Combustion Engine

H₂ICE: Hydrogen Fueled Internal Combustion Engine
H₂CIE: Hydrogen Fueled Compression Ignition Engine
H₂SIE: Hydrogen Fueled Spark Ignition Engine
MAHI: Mechanically Activated Hydrogen Injector
SFC: Specific Fuel Consumption
TE: Thermal Efficiency
VE: Volumetric Efficiency
RES: Renewable Energy Sources
HHV: Higher Calorific Value
LHV: Lower Calorific Value
GHG: Greenhouse Gases

CONFLICT OF INTEREST

The author stated that there are no conflicts of interest regarding the publication of this article.

CRediT AUTHOR STATEMENT

Ahmet Görgülü: Formal analysis, Writing-original draft, Visualization, Conceptualization, Validation Investigation, Supervision, Writing-Review and Editing, Funding acqusition.

REFERENCES

[1]   Luo Q he, Sun B gang. Inducing factors and frequency of combustion knock in hydrogen internal combustion engines. Int J Hydrogen Energy 2016;41:16296–305. https://doi.org/10.1016/J.IJHYDENE.2016.05.257.

[2]   Wróbel K, Wróbel J, Tokarz W, Lach J, Podsadni K, Czerwiński A. Hydrogen Internal Combustion Engine Vehicles: A Review. Energies (Basel) 2022;15:8937. https://doi.org/10.3390/en15238937.

[3]   Dash SK, Chakraborty S, Elangovan D. A Brief Review of Hydrogen Production Methods and Their Challenges. Energies (Basel) 2023;16:1141. https://doi.org/10.3390/en16031141.

[4]   Cetinkaya E, Dincer I, Naterer GF. Life cycle assessment of various hydrogen production methods. Int J Hydrogen Energy 2012;37:2071–80. https://doi.org/10.1016/J.IJHYDENE.2011.10.064.

[5]   Herdem MS, Mazzeo D, Matera N, Baglivo C, Khan N, Afnan, et al. A brief overview of solar and wind-based green hydrogen production systems: Trends and standardization. Int J Hydrogen Energy 2024;51:340–53. https://doi.org/10.1016/J.IJHYDENE.2023.05.172.

[6]   Yu M, Wang K, Vredenburg H. Insights into low-carbon hydrogen production methods: Green, blue and aqua hydrogen. Int J Hydrogen Energy 2021;46:21261–73. https://doi.org/10.1016/J.IJHYDENE.2021.04.016.

[7]   Zainal BS, Ker PJ, Mohamed H, Ong HC, Fattah IMR, Rahman SMA, et al. Recent advancement and assessment of green hydrogen production technologies. Renewable and Sustainable Energy Reviews 2024;189:113941. https://doi.org/10.1016/J.RSER.2023.113941.

[8]   Mulky L, Srivastava S, Lakshmi T, Sandadi ER, Gour S, Thomas NA, et al. An overview of hydrogen storage technologies – Key challenges and opportunities. Mater Chem Phys 2024;325:129710. https://doi.org/10.1016/J.MATCHEMPHYS.2024.129710.

[9]   Cui X, Su H-Y, Chen R, Yu L, Dong J, Ma C, et al. Room-temperature electrochemical water–gas shift reaction for high purity hydrogen production. Nat Commun 2019;10:86. https://doi.org/10.1038/s41467-018-07937-w.

[10]   Reitz RD. Directions in internal combustion engine research. Combust Flame 2013;160:1–8. https://doi.org/10.1016/J.COMBUSTFLAME.2012.11.002.

[11]   Schlapbach L, Züttel A. Hydrogen-storage materials for mobile applications. Nature 2001;414:353–8. https://doi.org/10.1038/35104634.

[12]   Bradley D, Lawes M, Liu K, Verhelst S, Woolley R. Laminar burning velocities of lean hydrogen–air mixtures at pressures up to 1.0 MPa. Combust Flame 2007;149:162–72. https://doi.org/10.1016/J.COMBUSTFLAME.2006.12.002.

[13]   Naber JD, Siebers DL. Hydrogen combustion under diesel engine conditions. Int J Hydrogen Energy 1998;23:363–71. https://doi.org/10.1016/S0360-3199(97)00083-9.

[14]   Gomes Antunes JM, Mikalsen R, Roskilly AP. An experimental study of a direct injection compression ignition hydrogen engine. Int J Hydrogen Energy 2009;34:6516–22. https://doi.org/10.1016/J.IJHYDENE.2009.05.142.

[15]   Hosseini SE, Butler B. An overview of development and challenges in hydrogen powered vehicles. Int J Green Energy 2020;17:13–37. https://doi.org/10.1080/15435075.2019.1685999.

[16]   Gurz M, Baltacioglu E, Hames Y, Kaya K. The meeting of hydrogen and automotive: A review. Int J Hydrogen Energy 2017;42:23334–46. https://doi.org/10.1016/J.IJHYDENE.2017.02.124.

[17]   Görgülü A. Hidrojenin Yakıt Olarak İçten Yanmalı Motorlarda Kullanımı ve Diğer Yakıtlarla Mukayesesi. Yök Tez 1994:1–261. https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=CY4OWm88FIK9HX-Q31ydNg&no=CY4OWm88FIK9HX-Q31ydNg (accessed November 1, 2024).

[18]   He L, Jingyuan L, Xiumin Y, Mengliang L, Tian Y. Numerical Study on Combustion and Emission Characteristics of a PFI Gasoline Engine with Hydrogen Direct-Injection. Energy Procedia 2019;158:1449–54. https://doi.org/10.1016/J.EGYPRO.2019.01.348.

[19]   Boretti A. Hydrogen internal combustion engines to 2030. Int J Hydrogen Energy 2020;45:23692–703. https://doi.org/10.1016/J.IJHYDENE.2020.06.022.

[20]   Hari Ganesh R, Subramanian V, Balasubramanian V, Mallikarjuna JM, Ramesh A, Sharma RP. Hydrogen fueled spark ignition engine with electronically controlled manifold injection: An experimental study. Renew Energy 2008;33:1324–33. https://doi.org/10.1016/J.RENENE.2007.07.003.

[21]   White CM, Steeper RR, Lutz AE. The hydrogen-fueled internal combustion engine: a technical review. Int J Hydrogen Energy 2006;31:1292–305. https://doi.org/10.1016/J.IJHYDENE.2005.12.001.

[22]   Navale SJ, Kulkarni RR, Thipse SS. An experimental study on performance, emission and combustion parameters of hydrogen fueled spark ignition engine with the timed manifold

injection system. Int J Hydrogen Energy 2017;42:8299–309. https://doi.org/10.1016/J.IJHYDENE.2017.01.059.

[23] Nieminen J, Dincer I. Comparative exergy analyses of gasoline and hydrogen fuelled ICEs. Int J Hydrogen Energy 2010;35:5124–32. https://doi.org/10.1016/J.IJHYDENE.2009.09.003.

[24] Verhelst S, Wallner T. Hydrogen-fueled internal combustion engines. Prog Energy Combust Sci 2009;35:490–527. https://doi.org/10.1016/J.PECS.2009.08.001.

[25] Verhelst S, Sierens R. Aspects concerning the optimisation of a hydrogen fueled engine. Int J Hydrogen Energy 2001;26:981–5. https://doi.org/10.1016/S0360-3199(01)00031-3.

[26] Stępień Z. A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges. Energies (Basel) 2021;14:6504. https://doi.org/10.3390/en14206504.

[27] Ghazal OH. Performance and combustion characteristic of CI engine fueled with hydrogen enriched diesel. Int J Hydrogen Energy 2013; 38:15469–76. https://doi.org/10.1016/j.ijhydene.2013.09.037.

[28] Habib MA, Abdulrahman GAQ, Alquaity ABS, Qasem NAA. Hydrogen combustion, production, and applications: A review. Alexandria Engineering Journal 2024;100:182–207. https://doi.org/10.1016/J.AEJ.2024.05.030.