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**Research Article**

# Experimental Study on Direct Hydrogen Injection in a SI Engine with a Mechanical Injector

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***Abstract*** – This study investigates the modification of a single-cylinder, air-cooled, four-stroke spark-ignition internal combustion engine for hydrogen direct injection using a mechanically actuated injector. The cylinder head was redesigned to integrate a mechanical hydrogen injector synchronized with the intake valve. To assess the injector's performance, various measurement instruments were installed on the test engine, ensuring the collection of key operational parameters. Safety mechanisms were implemented to guarantee a secure hydrogen injection process. The engine was tested under different throttle positions (20° to 40°) and speeds (1000-3500 rpm), with recorded data including torque, net mechanical output, specific fuel consumption, thermal efficiency, and volumetric efficiency. Results indicated that hydrogen operation yielded a torque range of 4-5 Nm, thermal efficiency (TE) between 32.2% and 34.9%, and specific fuel consumption (SFC) values ranging from 86 to 112 g/kWh at a 20° throttle angle. The maximum torque recorded was 8 Nm at 20° butterfly opening, with a specific fuel consumption of 930 g/kWh and thermal efficiency of 3.45%. The optimal operating conditions were identified at TE 34.91% with an SFC of 86 g/kWh at 1.2 Nm torque at a 20° throttle opening. Notably, issues such as knocking, pre-ignition, and backfire, which are common in hydrogen manifold injection systems, were not observed. This study introduces a novel approach, as prior research has not utilized a mechanically actuated hydrogen injector synchronized with the intake valve for direct hydrogen injection into the combustion chamber.

*Keywords – Hydrogen-Fueled Engine, Specific Fuel Consumption, Thermal Efficiency, Torque, Direct Injection, Mechanical Injector.*

## I. INTRODUCTION

Hydrogen-fueled internal combustion engines ($H_2$ICEs) have garnered interest due to their lower emissions compared to gasoline, propane, and diesel engines.[1], [2], [3].

Table 1. Combustion products of some fuels

| Fuel Type | g/1000 kcal | | | |
|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | CO | Particles |
| Diesel | 310 | 1.5 - 7.0 | 0.5 - 2.0 | 0.1 - 0.5 |
| Gasoline | 297 | 0.5 - 2.0 | 1.0 - 4.5 | 0.01 - 0.1 |
| LPG (Propane) | 271 | 0.2 - 1.2 | 0.3 - 1.5 | Very low |

Hydrogen offers key advantages for spark-ignition (SI) engines, including a low ignition temperature, a broad flammability range in fuel/air mixtures, and a high combustion speed. Additionally, hydrogen combustion generates no carbon dioxide (CO2) or unburned hydrocarbons (UHC) and results in lower nitrogen oxide (NOx) emissions. However, pre-mixing hydrogen with intake air before combustion can lead to backfire and knocking [4]. Another challenge is hydrogen's low calorific value per unit volume, which limits engine power output, especially at low pressures [5]. It is stated that hydrogen fueled engines will develop further and be widely used in the coming years [6]. Furthermore, hydrogen production remains costly, and its storage requires high safety standards and energy-efficient containment solutions. Intensive studies on hydrogen production methods and its use in internal combustion engines are ongoing [7]. Several hydrogen injection methods have been explored, including intake manifold injection, cold hydrogen injection into the combustion chamber, and dual-fuel configurations with gasoline. While hydrogen use in compression ignition (CI) engines is possible, it necessitates high-pressure injectors. [8]. The total carbon emissions from hydrogen production also make Life Cycle Analysis (LCA) critically important depending on production methods [9]. Hydrogen production from renewable energy sources is significant in terms of emissions reduction [10], [11], [12]. 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 [13]. 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 [14]. Fossil-fueled Internal Combustion Engines (ICE) produce Carbon Monoxide (CO), Nitrogen Oxides ($NO_x$), Unburned Hydrocarbons (UHC), Particulate Matter (PM), and Greenhouse Gases (GHG) as combustion products [15]. 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 [16]. Due to its high diffusivity, low ignition energy, and high flame speed relative to gasoline and methane, hydrogen is well-suited for SI engines [17]. 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 [13]. Hydrogen can also be used in Compression Ignition (CI) engines, where different injector types are employed to introduce high-pressure hydrogen into the cylinder [18]. Thus, in CI engines, injector design is as critical as engine structure [19]. 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 [20].

## II. MATERIALS AND METHOD

In this study, a single-cylinder, air-cooled gasoline ($C_8H_{18}$) engine was modified to operate with hydrogen. Various measuring devices and sensors were installed on the engine to monitor and record experimental data. Figure 1 shows the feeding scheme of hydrogen to the engine. The hydrogen gas used in the experiments were supplied in 150-bar pressure tubes, with a pressure-regulating device attached to ensure consistent pressure during testing. Pressure gauges (Figure 1, D, F) 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 flowmeter.

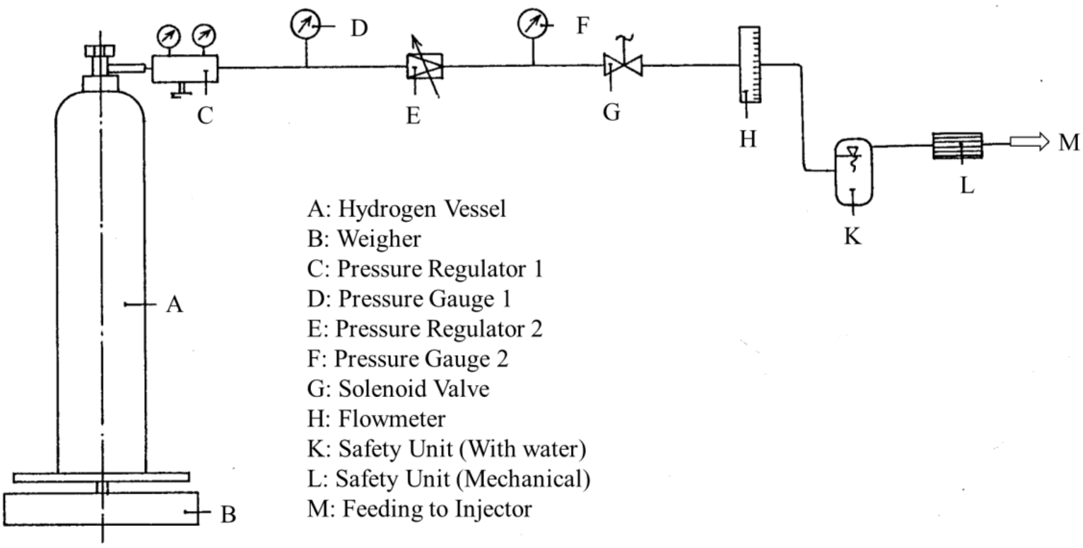


Figure 1. Experimental setup gas fuel supply equipment diagram and circuit equipment.

Hydrogen gas were tested as fuels in the engine. 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 (Figure 2, L, J, M). To prevent overheating, deformation, or jamming of the hydrogen injector, its body was cooled with externally supplied mains water (Figure 2, B, C). Additionally, the temperatures of the engine oil and exhaust gases were monitored with separate thermometers (Figure 2, E, H). 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 [21].

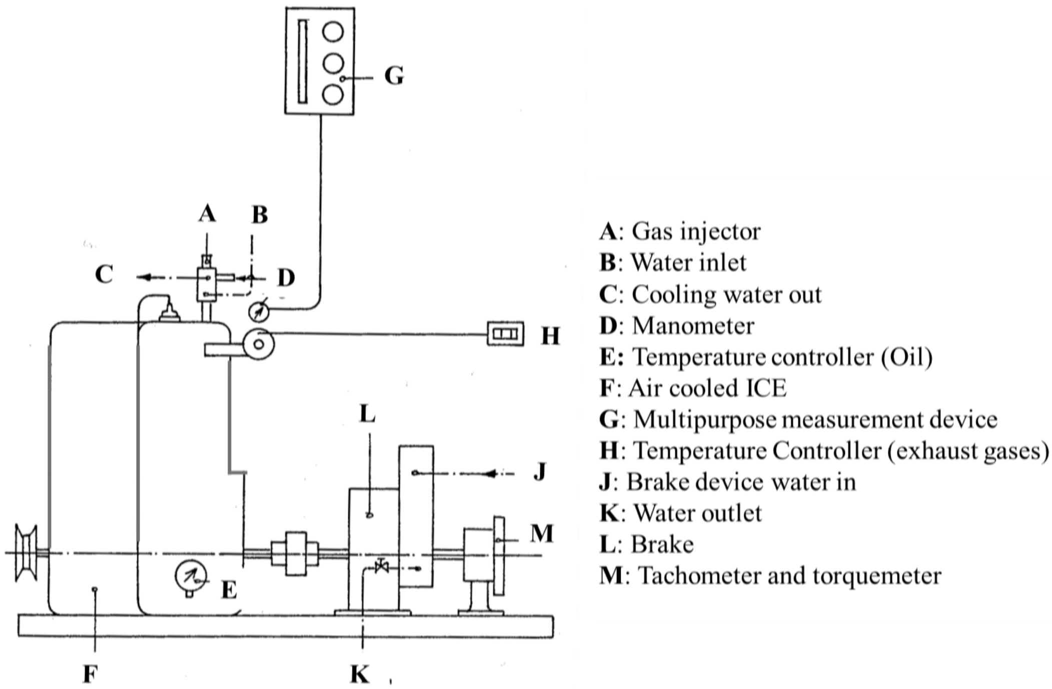


Figure 2. Schematic view of the experimental setup

In this study, a single-cylinder internal combustion, 4-stroke, air-cooled gasoline engine (Table 2) 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 3). The technical specifications of the test engine used in the experiments are given in Table 2.

Table 2. 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 |

The injector, which is opened by the intake valve, is mounted on the engine cylinder head (Figure 3, C). The torque meter (Figure 3, D) and tachometer (Figure 3, F), which measure two important performances of the engine, are mounted on the engine.

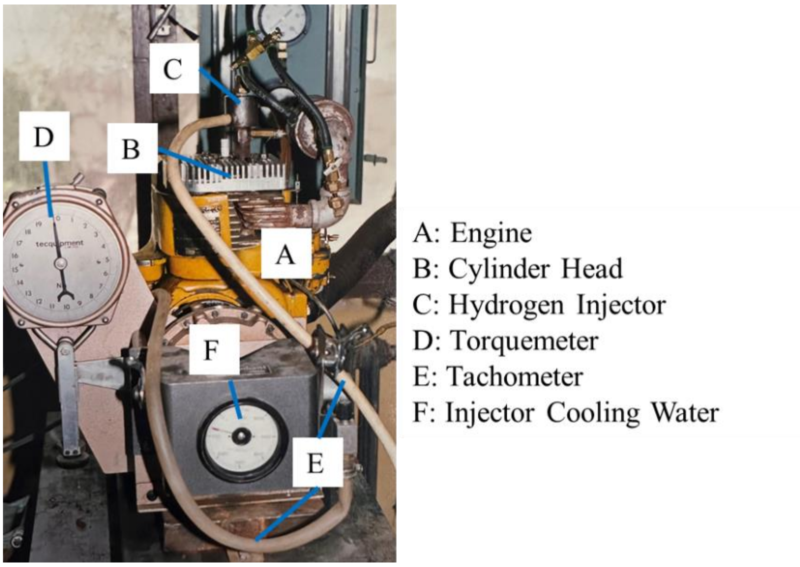


Figure 3. Single piston ICE, cylinder head, and injector

The injector's timing for intake valve opening can be adjusted by modifying its connection height to the cylinder head (Figure 4, H, K). A pressure spring (Figure 4, 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 4, a) blocks both the hydrogen inlet (Figure 4, D) and the gas flow channels (Figure 4, 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.

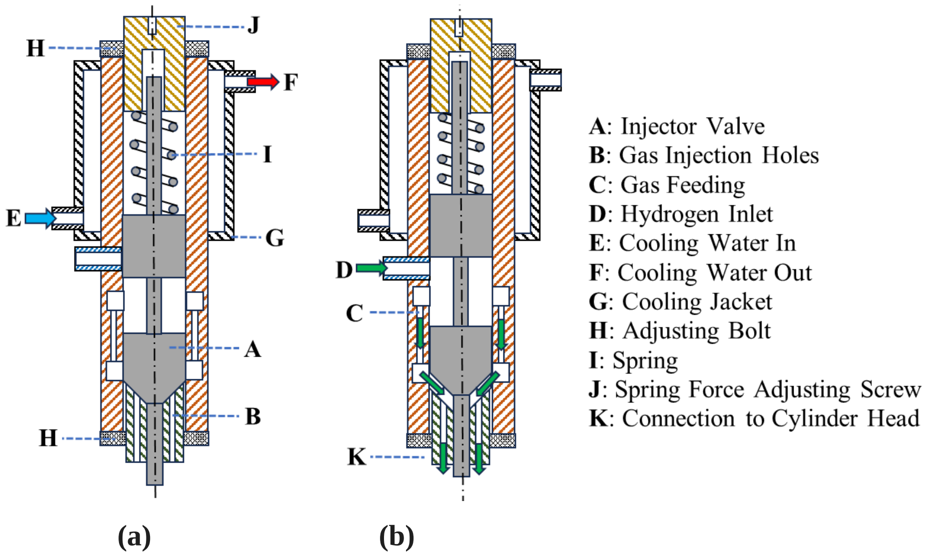


Figure 4. Hydrogen injector and working principle (a: Closed, b: Open)

A mechanically actuated hydrogen injector (MAHI) was designed and implemented for direct fuel injection into the combustion chamber. The closed (Figure 5, a) and open (Figure 5, b) positions of the injector are shown schematically in Figure 3. The injector is driven by the intake valve (Figure 5, b); it opens when the intake valve opens (Figure 5, b) and closes when the intake valve closes, aided by the spring mechanism (Figure 5, a).

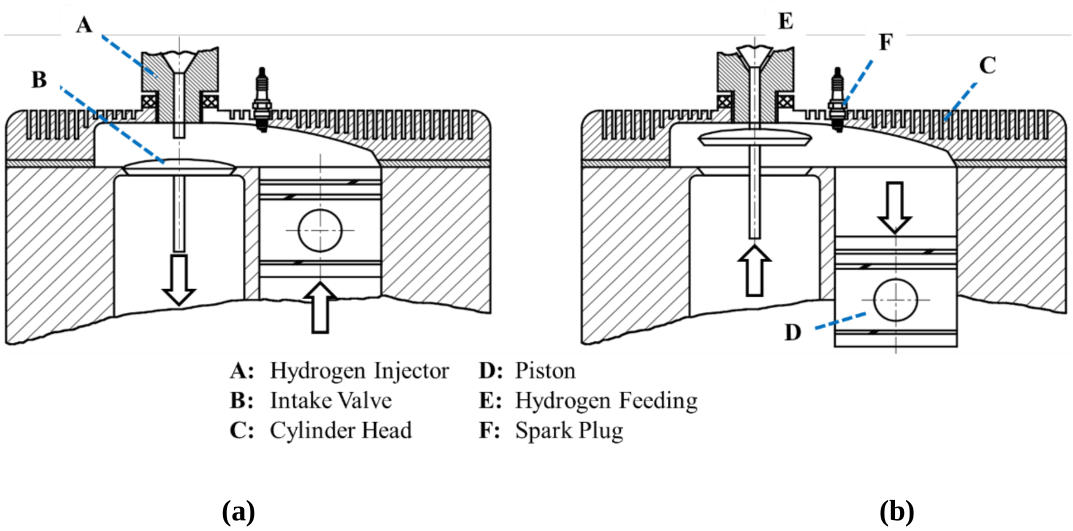


Figure 5. The cross-section of the combustion chamber and injection principle.

The design and main components of the hydrogen injector shown as a technical drawing in Figure 4 are presented in Figure 6. The injector is designed and constructed to inject hydrogen safely and directly into the combustion cell. The hydrogen pathway is sealed with 3 different surfaces for maximum tightness (Figure 6, A). The injector is normally closed by means of a compression spring (Fig. 6, I), which is opened by means of the suction valve's lever, and the hydrogen is pumped into the combustion chamber when the engine piston is in the suction position.

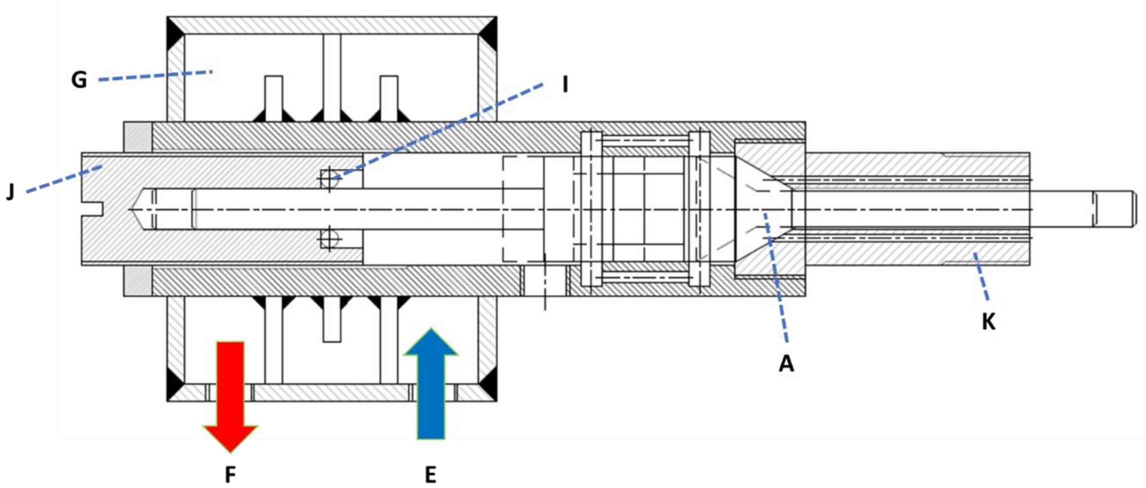


Figure 6. Mechanically activated hydrogen injector and main parts

The modified engine was tested with hydrogen, and all experimental data were recorded. During testing, the combustion air throttle angle was adjustable from 20º to 40º. The hydrogen consumption entering the engine was varied at each throttle angle, and the engine was tested at speeds ranging from 1000 to 3500 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 Thermal Efficiency (TE) and Volumetric Efficiency (VE) were also calculated.

## III. RESULTS

After conducting experiments with the modified gasoline engine redesigned to accommodate a gas fuel injector—additional tests were performed using the direct injection method into the combustion chamber with a specially developed injector (Figure 6). To evaluate engine performance, data on engine torque, brake power, specific fuel consumption, thermal efficiency (TE), and volumetric efficiency (VE) were analyzed. A specially designed mechanical injector (Figure 6) was developed to inject hydrogen directly into the combustion chamber. Hydrogen, stored in a cylinder at a pressure of 150 bar, was reduced to 0.25 bar by a pressure regulator before being introduced into the engine. This pressure remained constant throughout the experiments. The injector, which is normally closed due to spring pressure (Figure 5a), is mechanically actuated by the intake valve (Figure 5b), allowing hydrogen at 0.25 bar to be injected into the combustion chamber via the suction effect of the piston (Figure 5b). During the hydrogen-fueled experiments, the engine achieved its maximum torque within the 1500–2100 rpm range at an air throttle opening of 30º, as shown in Figure 7. The optimal brake power of 0.268 kW was recorded at 1600 rpm with a 30º throttle opening. However, tests were not conducted at throttle openings exceeding 40º due to poor engine performance under these conditions. This decline in performance was attributed to an insufficient supply of hydrogen in its gaseous phase at throttle openings above 40º.

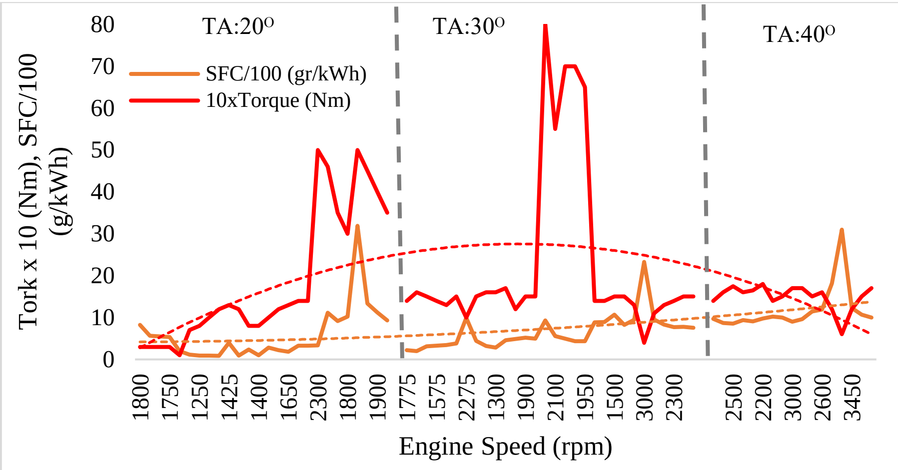


Figure 7. $H_2$ICE Engine speed, torque, SFC

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 1300-1775 rpm. The optimum operating conditions are observed at 1300-1600 rpm with 30° air throttle angle.

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 8. It is seen from the graphs given in Figure 8 that the optimum operating range of VE and TE occurs in a 20° air throttle angle at 1000-2300 rpm engine speed.

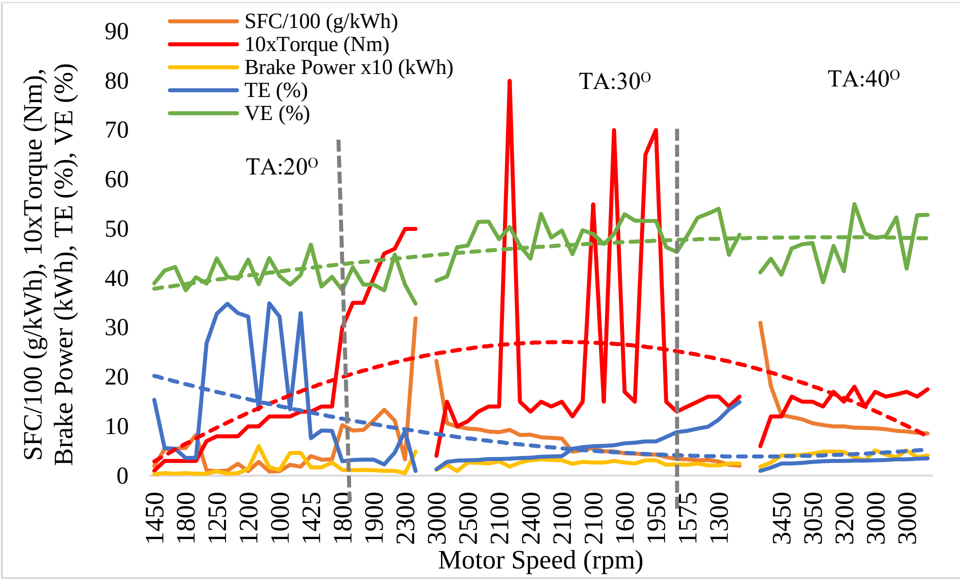


Figure 8. $H_2$ICE Full Engine performance variables

Table 4 indicates that under optimal conditions, volumetric efficiency (VE) ranges from 44.71% to 54.05%, while thermal efficiency (TE) varies between 9.4% and 14.9%. TE decreases inversely as VE increases, primarily due to the upper limit of the hydrogen/air mixture in its gaseous phase. To further analyze engine performance, a theoretical power calculation was conducted under ideal combustion conditions (piston diameter: 66.45 mm, stroke: 66.68 mm) for the 1800 rpm test condition (Table 5, Line 3). Assuming a hydrogen/air mixture ratio of 2 moles $H_2$ to 1 mole $O_2$, the theoretical power output was determined to be 0.1473 kW. However, the experimentally measured power for this condition was 0.207 kW, indicating that the mixture is being supercharged into the combustion chamber. The corresponding experimental data for this theoretical power value is recorded as 0.207 kW in Table 5, Test No. 3

Table 5. 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 | 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 optimal performance was achieved within the 1300–1775 rpm range at a 30º air throttle opening. The highest brake power, 0.534 kW, was recorded at a 40º throttle opening and 3000 rpm, with a torque of 1.7 Nm, a brake power of 0.414 kW, and a specific fuel consumption (SFC) of 0.93. Thermal efficiency (TE) reached its peak value of 34.91% at a 20º throttle opening and 1100 rpm, with a torque of 1.2 Nm and a brake power of 0.138 kW. Meanwhile, at a 30º throttle opening and 1825 rpm, with a torque of 1.7 Nm and a brake power of 0.325 kW, TE was measured at 6.94%, while volumetric efficiency (VE) was 55.16%. A summary comparing key performance parameters is provided in Table 5.

## IV. DISCUSSION

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 [22]. Ho Lung Yip et al have made a review on injector types and combustion. It has been stated that injections made through the intake manifold cause pre-ignition, knocking, backfiring, low volumetric efficiency and compression loss problems. They stated that the pilot fuel ignition method is more successful than spark ignition [23]. 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 [24]. 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 $H_2$ICE 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 [25]. Another study compared gasoline and hydrogen in spark SI engines with timed injections into the intake manifold via electronic control units. In this study, propane showed higher performance in the direct gas fuel injection method into the combustion chamber with the help of a mechanical injector due to its higher lower heating value in the gas phase. Propane showed 2.65 times higher performance in torque, 1.4 times in brake power, 1.3 times in thermal efficiency, and 1.4 times in volumetric efficiency compared to hydrogen. 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 [26], [27]. 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 [28]. 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 [29] 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 [30].

## V. CONCLUSION

Experiments were conducted on a modified single-cylinder, four-stroke, air-cooled spark-ignition (SI) internal combustion engine (ICE) using hydrogen as fuel. The tests were performed at air throttle angles ranging from 20º to 40º and engine speeds between 1000 and 3500 rpm. At a 20º throttle angle, hydrogen operation resulted in a torque of 4–5 Nm, a thermal efficiency (TE) of 32.2% to 34.9%, and a specific fuel consumption (SFC) of 86–112 g/kWh. The maximum torque recorded was 8 Nm at a 20º throttle opening, with an SFC of 930 g/kWh. At this point, the thermal efficiency was measured at 3.45%. The optimal operating conditions were determined as a TE of 34.91% with an SFC of 86 g/kWh at a torque of 1.2 Nm and a 20º throttle valve opening. During the tests, common issues associated with hydrogen injection into the intake manifold such as knocking, pre-combustion, and backfire were not observed. These findings suggest that achieving the same torque and power with gaseous hydrogen, under the same cylinder volume, is unlikely unless the hydrogen pressure is increased. An alternative approach could be to enlarge the cylinder volume. For safety reasons, hydrogen was injected into the combustion chamber at a pressure of 0.25 bar in these experiments. However, further tests at higher hydrogen pressures could provide additional insights into performance improvements.

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## 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
**$H_2$ICE**: Hydrogen Fueled Internal Combustion Engine
**$H_2$CIE**: Hydrogen Fueled Compression Ignition Engine
**$H_2$SIE**: Hydrogen Fueled Spark Ignition Engine
**MAHI:** Mechanically Activated Hydrogen Injector
**SFC**: Specific Fuel Consumption
**TE**: Thermal Efficiency
**TA**: Throttle Angle
**VE**: Volumetric Efficiency
**RES:** Renewable Energy Sources
**HHV:** Higher Calorific Value
**LHV:** Lower Calorific Value
**GHG:** Greenhouse Gases

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