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RESEARCH ARTICLE

Experimental Study on Direct Injection of Propane and Hydrogen in a SI Engine with a Mechanical Injector

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Abstract

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In this study, a single-cylinder, air-cooled, four-stroke, spark-ignition internal combustion engine was modified to operate with both gaseous propane and hydrogen fuels. The cylinder head was redesigned, and a mechanically actuated hydrogen injector was integrated into the system. Various measurement instruments were installed on the test engine to record critical operational parameters for comparative analysis. To ensure safe fuel injection process, the necessary safety mechanisms were implemented. Initially, the engine was tested with propane under throttle positions ranging from 20° to 90° (in increments of 10°) and speeds between 1000 and 4300 rpm, recording values for torque, net mechanical output, fuel consumption per unit output, engine thermal efficiency, and engine volumetric efficiency. The same parameters were subsequently measured while operating with gaseous hydrogen. Optimal performance for propane was observed at throttle openings of 80° and 90°, within the speed range of 1600–1850 rpm, while hydrogen exhibited the most favorable results at 30° throttle opening and speeds between 1300 and 1775 rpm. When the performance of both fuels was compared, it was found that hydrogen operation resulted in a 27.8% reduction in mechanical output and a 62.2% decrease in engine torque. This decline is attributed to hydrogen's lower volumetric energy density, which, under identical pressure and temperature conditions (1 bar, 20°C), is approximately 2,850 kcal/m³, whereas propane's lower heating value is 22,800 kcal/m³. Propane was supplied to the engine at a regulated pressure of 1.5 bar. Throughout the experimental procedures, common challenges associated with hydrogen manifold fuel injection, such as knocking, pre-ignition, and backfire, were not observed. This study presents an innovative approach, as no previous research has employed a mechanically actuated hydrogen injector synchronized with the intake valve for direct hydrogen injection into the reaction zone.

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Introduction:-

Propane-fueled internal combustion engines are preferred because they cause less emissions than gasoline and diesel-fueled engines (Gibson et al., 2011; Sulaiman et al., 2013; Woo Jeong et al., 2024). Hydrogen-fueled engines are attractive due to their lower exhaust emissions compared to fossil-fuel internal combustion engines. Table 1 shows the combustion products produced by propane and hydrogen per 1000 kcal of energy compared to gasoline.

Table 1. Combustion products of some fuels

Fuel Type	g/1000 kcal		
	CO_2	CO	NO_x
Propane (C_3H_8)	~270	~140	0.3 - 0.6
Gasoline (C_8H_{18})	~300	~170	0.5 - 1.5
Hydrogen (H_2)	0	0	0.07 - 0.3

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 (Luo & Sun, 2016). Engine output power is limited by the low calorific value per unit volume of gaseous hydrogen, especially at low pressures (Wróbel et al., 2022). Additionally, as hydrogen does not naturally exist as a molecular element, its production is costly, requiring extraction from various sources through different methods (Dash et al., 2023). The total carbon emissions from hydrogen production also make Life Cycle Analysis (LCA) critically important depending on production methods (Cetinkaya et al., 2012). Hydrogen production from renewable energy sources is significant in terms of emissions reduction (Herdem et al., 2024; Yu et al., 2021; Zainal et al., 2024). 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 (Mulky et al., 2024). 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 (Cui et al., 2019). 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 (Reitz, 2013). 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 (Schlapbach & Züttel, 2001). Due to its high diffusivity, low ignition energy, and high flame speed relative to gasoline and methane, hydrogen is well-suited for SI engines (Bradley et al., 2007). 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 (Mulky et al., 2024). Hydrogen can also be used in Compression Ignition (CI) engines, where different injector types are employed to introduce high-pressure hydrogen into the cylinder (Naber & Siebers, 1998). Thus, in CI engines, injector design is as critical as engine structure (Gomes Antunes et al., 2009). 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 (Gurz et al., 2017).

Materials and Methods:

In this study, a single-cylinder, air-cooled gasoline (C_8H_{18}) engine was modified to operate with both propane (C_3H_8) and gaseous fuels. Various measuring devices and sensors were installed on the engine to monitor and record experimental data. Figure 1 shows the feeding scheme of propane and hydrogen fuels to the engine. The propane and 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.

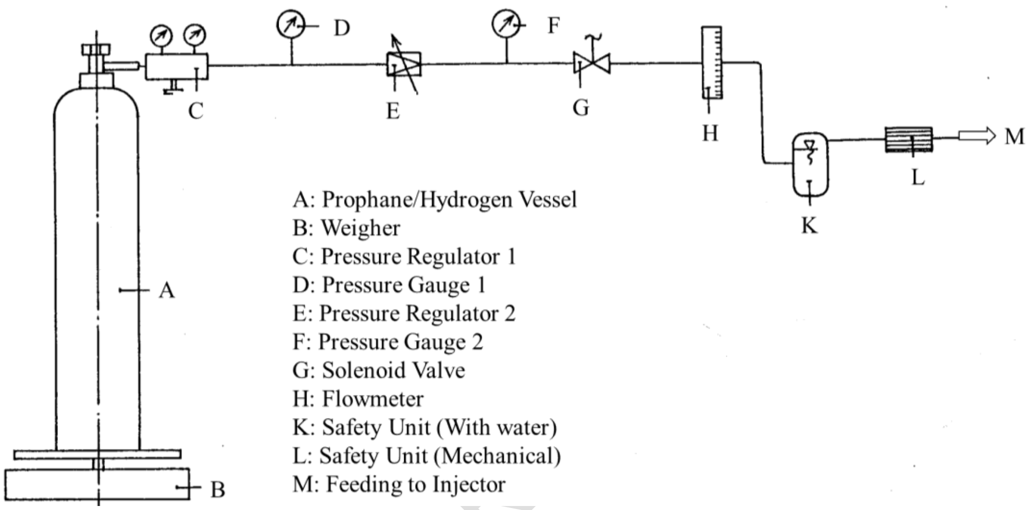


Figure 1. Experimental setup gas fuel supply equipment diagram and circuit equipment

Both propane and hydrogen gas were tested as fuels in the same engine, with comparisons made between engine performance and efficiency for each fuel type. 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 (Görgülü, 1994).

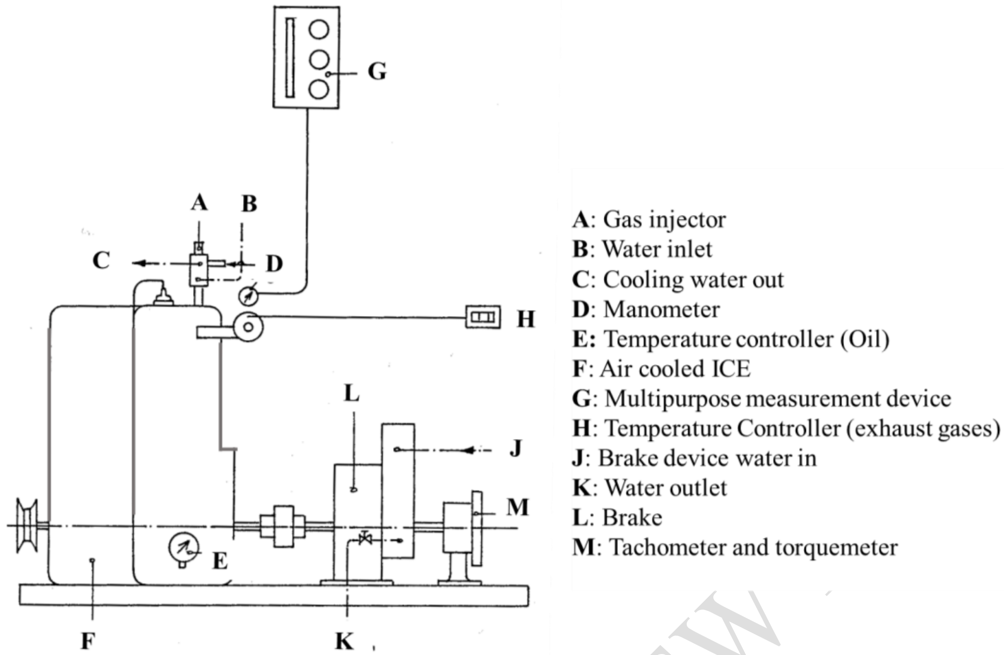


Figure 2. Schematic view of the experimental setup

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 propane and 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.

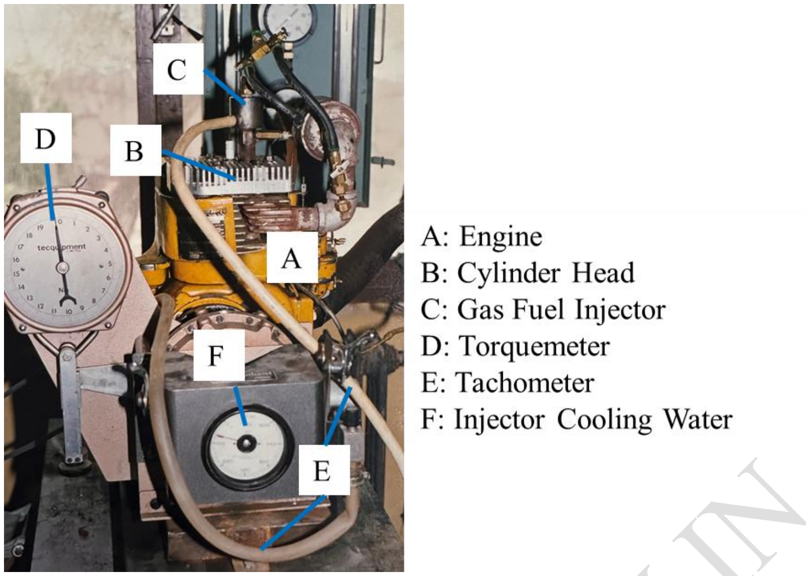
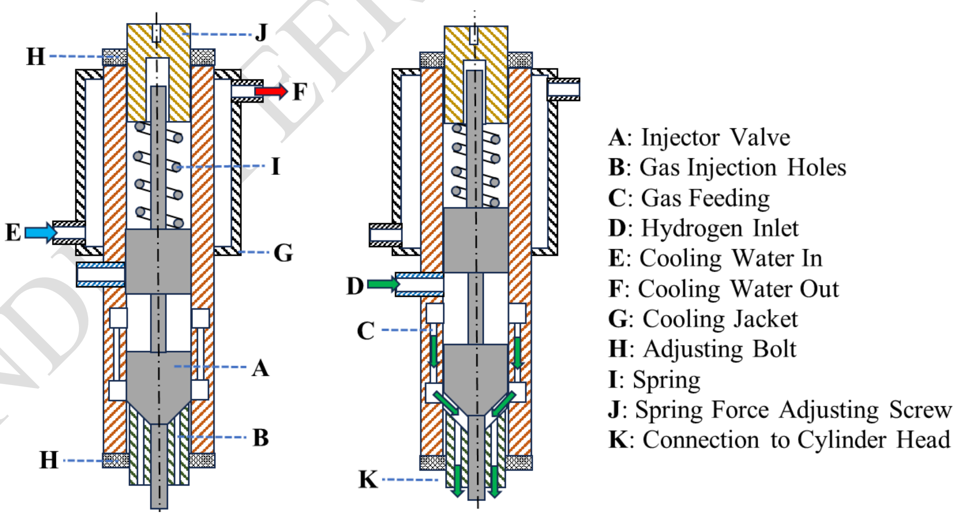


Figure 3. Single piston ICE, cylinder head, and injector

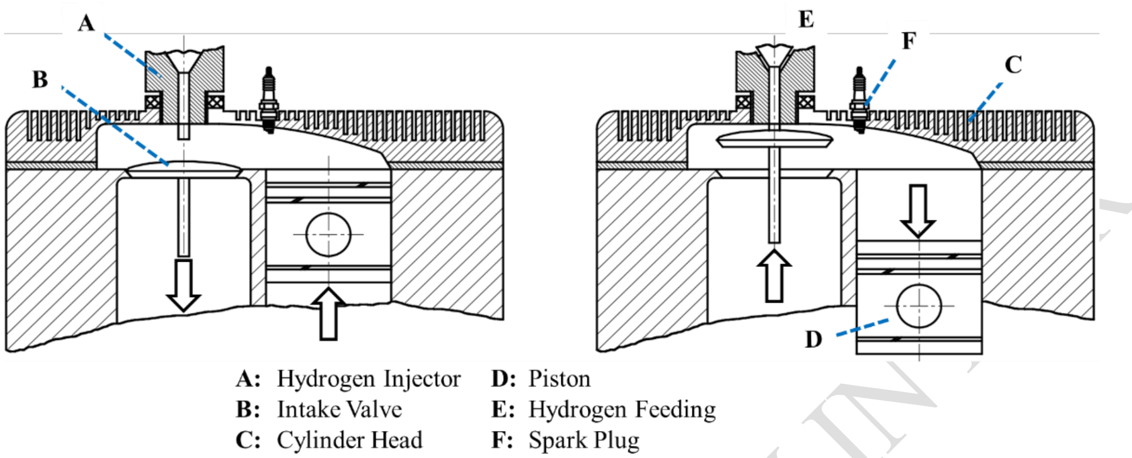
The injector's timing for intake valve opening can be adjusted by modifying its connection height to the cylinder head (Figure 4, H, K). A pressure spring (Figure 4, I) closes the injector, and the spring pressure can be fine-tuned to completely seal the hydrogen path (Figure 3, J). To ensure complete 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.



(a) (b)

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).



(a) **(b)**

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

The design and main components of the gas fuel injector shown as a technical drawing in Figure 4 are presented in Figure 6.

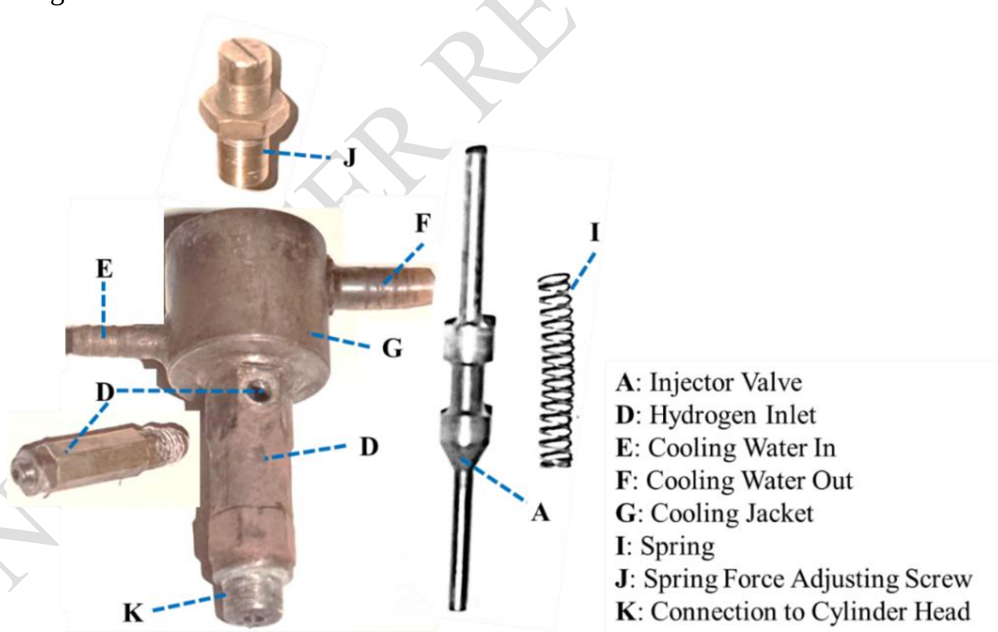


Figure 6. Mechanically Activated Gas Fuel Injector and main parts

The modified engine was first tested with propane, 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 4300 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. The recorded and calculated data were then compared to assess the engine's performance when operating with propane versus hydrogen.

Results and Discussion:-

Experimental analysis and results of GICE:-

To establish a baseline with propane for the modified engine, experiments were conducted at throttle angles of 30º-90º and engine speeds between 1000 and 4300 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 2, L, M). 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, Thermal Efficiency (TE), Volumetric Efficiency (VE), Specific Fuel Consumption (SFC), and excess air coefficient were calculated. In Figure 7, from left to right, the power curves for torque values obtained at engine speeds of 1300-3900 rpm for throttle openings of 30º, 40º, 50º, 60º, 70º, 80º, and 90º are shown.

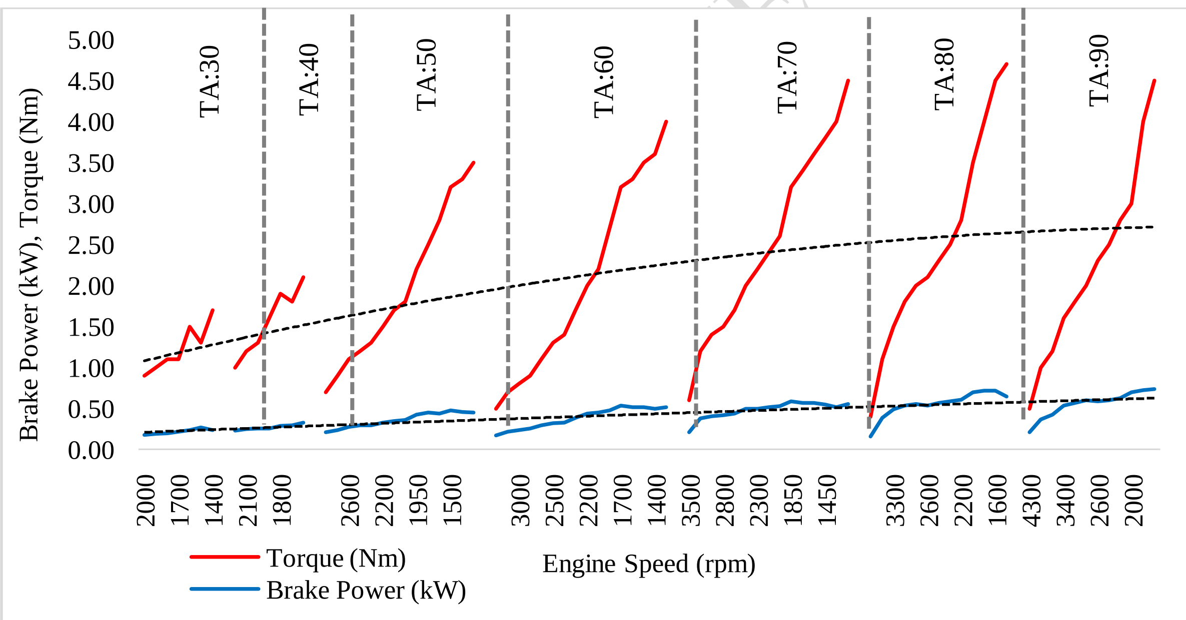


Figure 7. PICE Engine speed, torque, and Brake power

In Figure 7, the peaks in the curves from left to right correspond to the degree of Throttle Angle (TA) (30-90º). The summary table derived from the data tables (Table 3, lines 5-6-8) indicates that the engine achieves optimal torque performance at throttle openings of 70º, 80º, and 90º, within the speed range of 1250-1650 rpm.

Table 3. Optimum performance variables of PICE

Test No	Throttle Angle (º)	Engine Speed (rpm)	Torque (Nm)	Brake Power (kW)	SFC (g/kWh)	TE (%)	VE (%)
1	60	1500	3.50	0.52	165.6	46.4	14.6
2	60	1400	3.60	0.50	172.5	44.5	15.7
3	60	1300	4.00	0.52	167.2	45.9	14.6
4	70	1300	4.00	0.52	271.7	26.7	28.3
5	70	1250	4.50	0.56	251.1	27.7	30.6
6	80	1600	4.50	0.72	206.3	37.2	30.6
7	90	1850	4.00	0.73	210.5	36.5	35.0
8	90	1650	4.50	0.74	175.6	43.7	39.3

The highest TE values were obtained at 60^{O} air inlet opening and 1300-1500 rpm speed. The highest torque values occurred at 1250-1650 rpm (Table 3, tests; 5,6,8). The region marked in green in the graph in Figure 8 represents the range where both engine torque and power are at their optimum. The SFC data for the engine operating with propane, measured at air throttle openings of 30-90º (9 angles) and engine speeds from 1000 to 4300 rpm, are presented in Figure 8. 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 8.

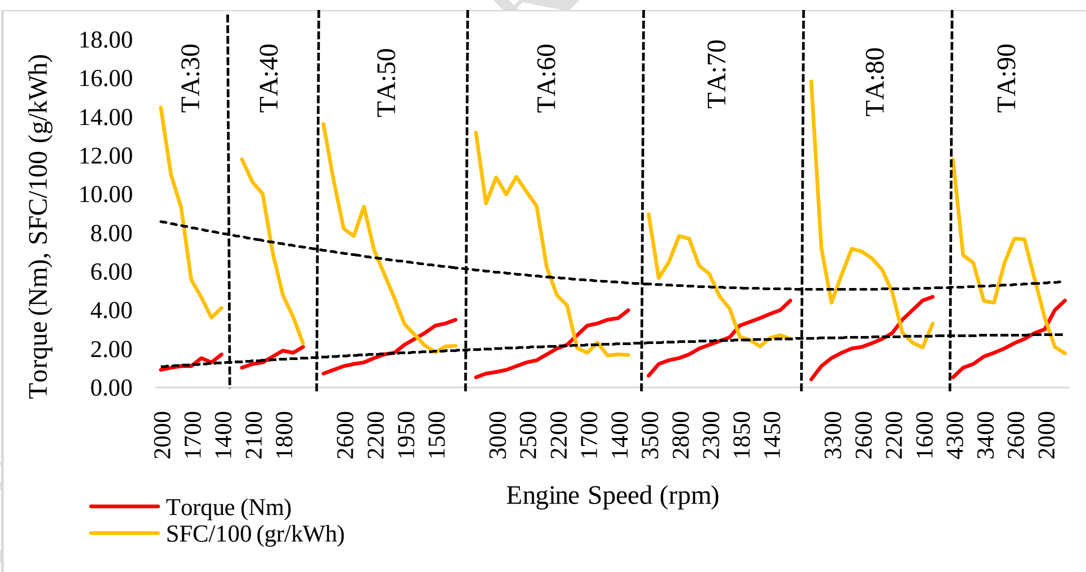


Figure 8. PICE Engine speed, torque, SFC

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 9 and Table 3, the optimum operating conditions for the engine running on propane are found at air throttle openings of 60º, 80º, and 90º, and within the speed range of 1400-4300 rpm. The engine's TE was determined to range from 43.7% to 46.4%, while its VE ranged from 14.6% to 39.3% (Table 3).

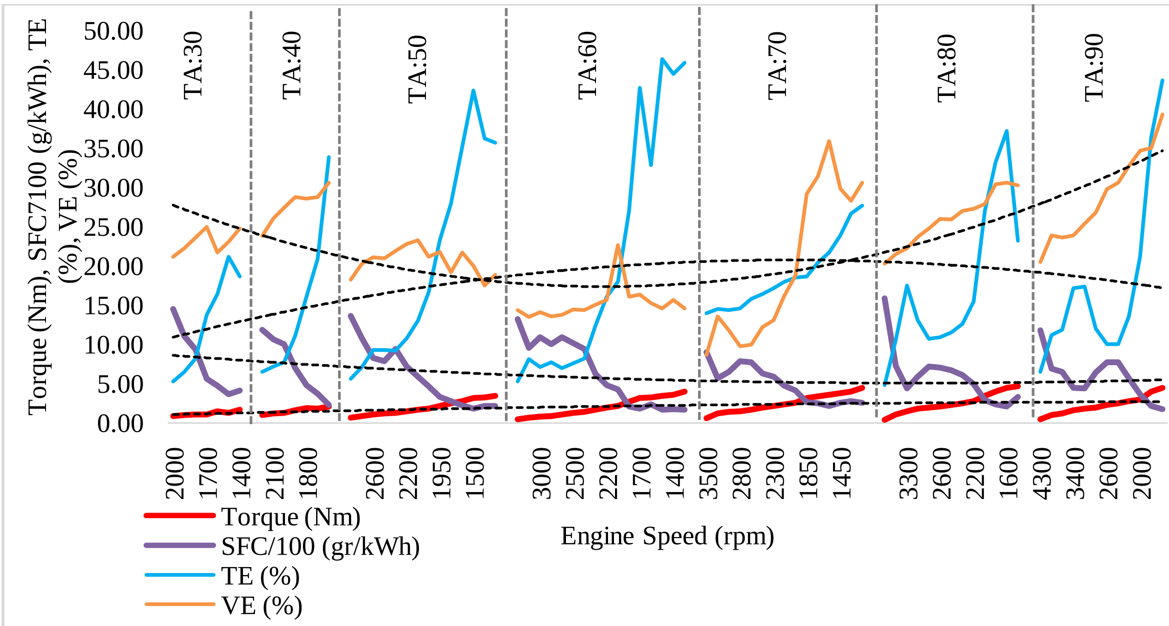


Figure 9. GICE Engine speed, Torque, SFC, TE, VE

In the experiments conducted with propane, the most optimal operating conditions were found at air throttle openings of 60º to 90º and engine speeds between 1500 and 1650 rpm. The highest torque of 4.5 Nm was achieved at 70-80-90º throttle opening and 1250-1600-1650 rpm, with a brake power of 0.56-0.74 kW and a SFC of 175,6 to 251.1 g/kWh. The highest brake power of 0.74 kW was observed at 90º throttle opening and 1650 rpm, with a torque of 4.5 Nm and an SFC of 175.6 g/kWh. The highest TE of 46.4% was recorded at 60º throttle opening and 1500 rpm, with a torque of 3.5 Nm and a brake power of 0.52 kW. The highest VE of 36.3% was achieved at 90º throttle opening and 1650 rpm, with a torque of 4.5 Nm, brake power of 0.74 kW, and a TE of 43.7%.

Experimental analysis and results of H_2ICE:-

After the experiments with the modified gasoline engine, which was redesigned to accommodate the gas fuel injector, additional tests were conducted using the direct injection method into the combustion chamber with the specially developed injector (Figure 6). To facilitate comparisons with the propane-fueled engine, data on engine torque, brake power, specific fuel consumption, TE, and VE were considered. The specially designed mechanical injector (Figure 6) 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 5, a), is mechanically opened by the intake valve (Figure 5, b), and hydrogen at 0.25 bar is injected into the combustion chamber using the suction effect of the piston (Figure 5, b).

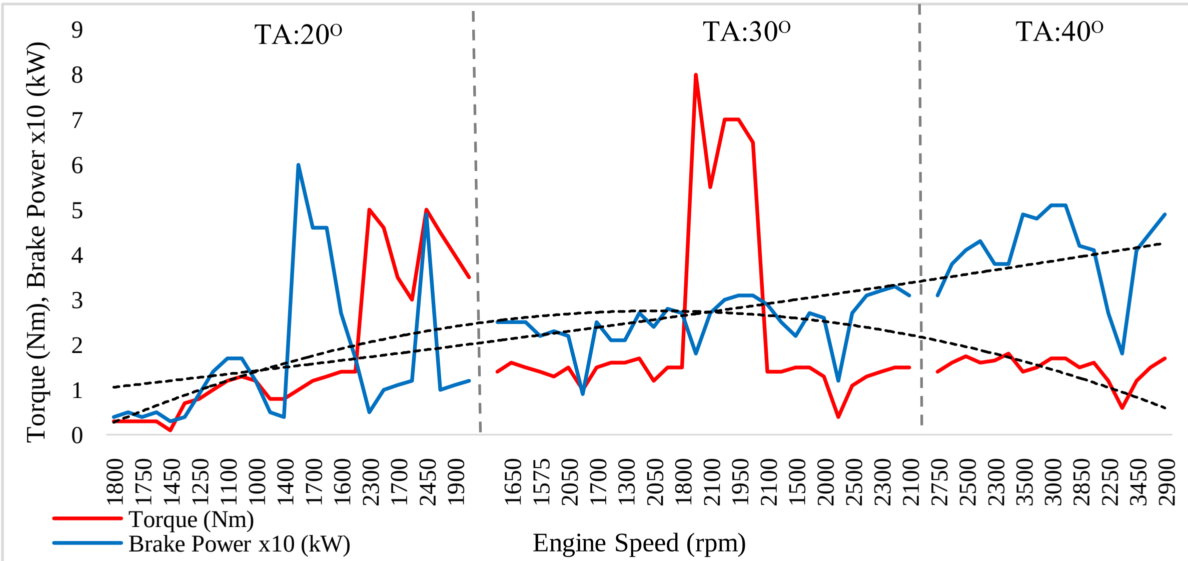


Figure 10. H_2ICE Engine speed; Torque, Brake power

In the experiments conducted with hydrogen, Figure 10 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.

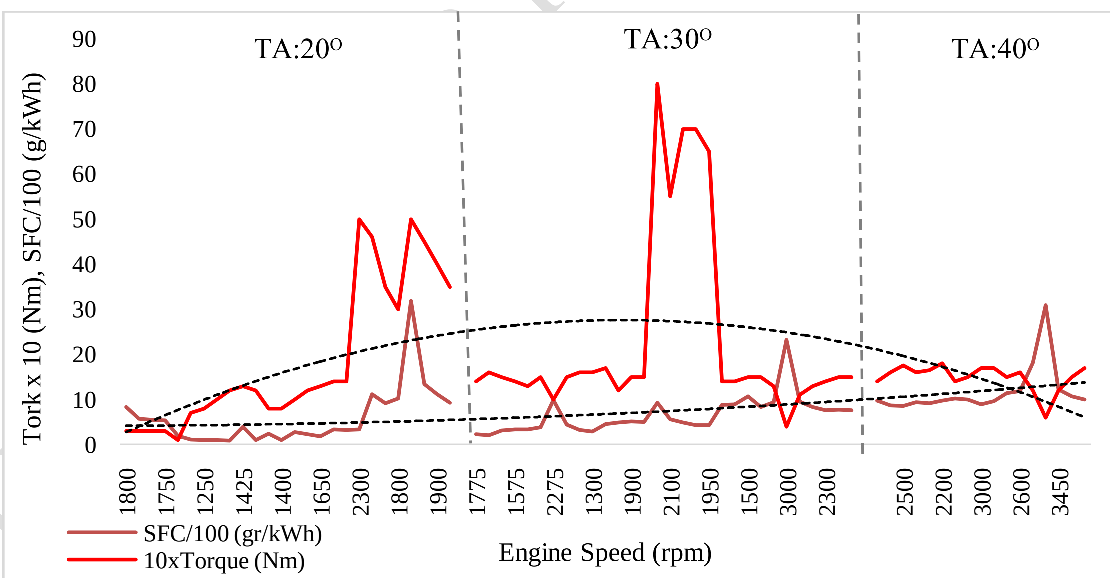


Figure 10. H_2ICE Engine speed, torque, SFC

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 30º air throttle angle.

Table 3. 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	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 a 30° air throttle angle at 1300-1775 rpm engine speed.

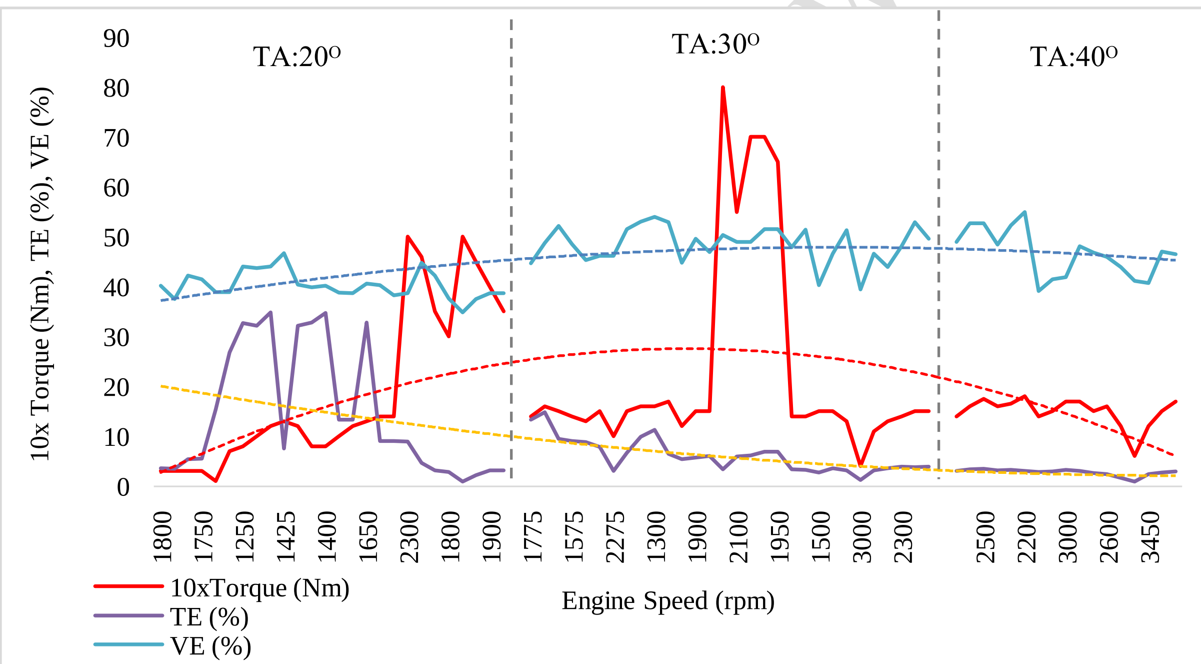


Figure 11. H_2ICE Engine speed, torque, TE, VE

Table 4 shows that under optimum conditions, the VE ranges from 44.71% to 54.05%, while the TE varies between 9.4% and 14.9%. 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 5, 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 5, Test No: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 5. 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 30º air throttle opening. The highest brake power of 0.534 kW was measured at 40º, 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 20º, 1100 rpm, with 1.2 Nm torque and 0.138 kW brake power. At 30º, 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.

Comparative performance analysis of GICE and H_2ICE:-

The important performance data obtained as a result of operating the engine with propane 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 6. Compared to propane, hydrogen's Engine Torque was 25.56%, and Engine Brake Power was 20.46%. TE was 67.92%, and VE was 176%.

Table 6. Comparisons of critical engine parameters.

Specifications	Unit	PICE	H_2ICE	%
Torque	Nm	4.50	1.7	37.8
Brake Power	kW	0.74	0.53	72.2
SFC	g/kW	165.6	0.93	
TE	%	46.40	34.91	75.2
VE	%	39.30	55.16	140.2

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 (Hari Ganesh et al., 2008). 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 (White et al., 2006). 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 (Nieminen & Dincer, 2010; Sebastian Verhelst & Wallner, 2009). 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 (S. Verhelst & Sierens, 2001). 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 (Hosseini & Butler, 2020) 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 (Stępień, 2021). 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 (Ghazal, 2013).

Conclusion:-

Experiments were conducted on a modified single-cylinder, 4-stroke, air-cooled spark-ignition (SI) internal combustion engine (ICE) using both propane and hydrogen as fuels. The tests were carried out at air throttle angles ranging from 20º to 90º and engine speeds between 1000 and 4300 rpm. When comparing the performance of propane and hydrogen on the same engine, it was found that the use of gaseous hydrogen resulted in a significant loss of engine power (27.8%) and torque (62.2%). This reduction is attributed to the lower calorific value of hydrogen in its gaseous phase, which is approximately 2.850 kcal/m^3 at 1 bar and 20ºC, compared to propane's calorific value of around 22,800 kcal/m^3 (Habib et al., 2024). 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.

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Nomenclature:-

ICE: Internal Combustion Engine
PICE: Propane Fueled 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_2ICE: Hydrogen Fueled Internal Combustion Engine
H_2CIE: Hydrogen Fueled Compression Ignition Engine
H_2SIE: 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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