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Research paper

Influence of hydrogen addition on the performance and emissions of gasoline engine

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ABSTRACT

To support the gradual shift toward hydrogen-enriched hybrid combustion engines, this study examines the changes in engine performance, combustion characteristics, and emission profile of a gasoline engine when hydrogen is added. Experimental tests for pure gasoline were collected to establish baseline performance data with a laboratory test rig equipped with a single-cylinder, air-cooled gasoline engine operating between 1400 rpm and 3600 rpm at full load, while hydrogen addition was investigated separately through Diesel-RK numerical simulations. Hydrogen addition to gasoline was evaluated at volumetric ratios of 5 %, 10 %, and 15 %. The analysis focused on brake power, torque, brake-specific fuel consumption, brake thermal efficiency, and nitrogen oxide (NO_x) emissions. The results showed that adding 5 % hydrogen improved brake power by 8 % and reduced brake-specific fuel consumption by 7.5 % compared to pure gasoline. Torque values increased by 17 % and 22 % as the hydrogen content in blends grew from 10 % to 15 %, respectively. The octane number required to prevent knocking decreased by 4 % through 10 % hydrogen addition and by 8 % with 15 % hydrogen. Using fuel blends containing 5 %, 10 %, or 15 % hydrogen reduced nitrogen oxide emissions to 40 %, 65 %, and 77 %, respectively. However, at high engine speeds, brake power and thermal efficiency decreased when provided with excessive hydrogen addition, caused by air–fuel mismatch and incomplete combustion processes.

1. Introduction

In response to growing worldwide concerns about climate change and the depletion of fossil fuels, efforts are underway to switch to greener, more sustainable energy sources [1]. Internal combustion engines (ICEs) and stationary power production are among potential uses for hydrogen as an alternative fuel because of its availability and the fact that it produces no emissions when used. The use of hydrogen in ICEs has several benefits, including lower emissions of pollutants and greenhouse gases, increased combustion speed, and high efficiency [2]. Recent studies also highlight hydrogen as a central component of future sustainable energy systems, particularly when integrated with renewable energy sources and green electrolysis technologies [3,4]. Hydrogen presents unique issues in engine design, operation, and safety due to its broad ignition range, low ignition energy, and fast flame speed, among other unusual qualities [5]. To overcome these obstacles, advanced engine technologies are needed that boost performance, efficiency, and emissions control while also improving our understanding of hydrogen combustion and how it mixes with traditional fuels.

Numerous studies in the scientific literature have explored the effects of utilizing hydrogen and mixing it with traditional fuels in ICEs, focusing on power output and emissions. Studies have investigated ways to address the challenges related to hydrogen utilization [6]. For instance, Jayaprabakar et al. [7] explored the possibilities of hydrogen enrichment in ICEs, highlighting that hydrogen has the ability to decrease emissions and enhance performance, even though there are some challenges, including low power output and storage issues. The research indicated that incorporating hydrogen can lead to a reduction in nitrogen oxide (NO_x) emissions by as much as 80 %, a decrease in carbon dioxide (CO₂) emissions by up to 20 %, and an enhancement in fuel efficiency by 10 %. Nonetheless, their findings indicated that a hydrogen-powered engine produces less power than a gasoline-powered engine.

Similarly, research by Ji et al. [8] found that hydrogen addition in a gasoline direct injection engine decreased emissions of hydrocarbons (HC) by 33.10 % and carbon monoxide (CO) by 18.28 %, while also dramatically lowering particles in suspension. Adding hydrogen, nevertheless, resulted in a rise in NO_x emissions. Wang et al. [9]

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reported the effects of hydrogen-and biodiesel blends on vibration and noise in highway vehicle engines, with increasing biodiesel proportions, vibration was reduced by 15 % and noise by up to 6 dB. The impact of hydrogen with natural gas formulations was studied by Ingo et al. [10], determining an optimal blend of 13.4 % hydrogen to meet engine gas quality standards. This combination satisfies the Euromot standards for a methane number of 70.0 or more and a Wobbe index ranging from 49 to 52.7 MJ/m³. With a thermal efficiency of 38.5 % and the lowest emissions of HC and CO, a mixture of 20 % hydrogen and 80 % isooctane produced the best engine performance, according to research by Ayisi et al. [11] that examined the combustion, performance, and emissions characteristics of a spark ignition engine powered by various n-heptane, isooctane, ethanol, methanol, and hydrogen blends. On the other hand, NO_x emissions were greatest in this combination.

By substituting varying amounts of hydrogen for diesel fuel, Catapano et al. [12] studied hydrogen combustion in a compression ignition engine. It can be seen from the result that an increased replacement quantity shortens the ignition delay, quickens the rate of heat release, and increases the peak in-cylinder pressure. When the engine operates on hydrogen only, the brake thermal efficiency (BTE) reaches its maximum value of 41.5 %. On the other hand, smoke emissions are drastically reduced, but NO_x emissions also increase with an increase in the level of hydrogen replacement. According to Tsujimura and Suzuki [13], hydrogen can decrease CO emissions by up to 80 % and increase the BTE by 10 %. It was also observed that the lean working limit of the engine increases with the addition of hydrogen, thus opening a larger range of possible air-fuel mixes. Different fuel and mixture conditions of hydrogen in a commercial stationary power generator are experimentally explored by Yabcioglu and Dincer [14] to develop its operating regime.

Al-Dawody et al. [15] studied the effect of oxy-hydrogen (HHO) gas on single-cylinder diesel combustion characteristics using the Russian simulation software Diesel-RK model. The results showed that 10 % HHO gas improves thermal efficiency, reduces fuel consumption by up to 20 %, and increases peak combustion pressure and brake power by 10 % compared to diesel fuel without HHO. Similarly, Flaïh et al. [16] studied the performance of various volumetric blends of water ammonia solution (WAS) and gasoline fuel on spark ignition engines. The investigation was done numerically using Diesel-RK software.. The results obtained from this numerical study indicate small reductions in combustion pressure, heat release rate, and burning combustion temperature. On the other hand, the WAS blends increase knock resistance and reduce exhaust gas temperature. 20 % WAS blends showed higher BTE and brake-specific fuel consumption (BSFC). Erdemir [17] studied the feasibility of using hydrogen mixtures with gasoline, methane, and propane in commercial gasoline generators. The results indicate that increasing hydrogen content by 20 % reduced CO₂ emissions by 42.8 %, 46.9 %, and 37.7 %, while CO emissions were reduced by 44.8 %, 50 %, and 40 % for gasoline, propane, and methane, respectively. Furthermore, increasing hydrogen content decreases BSFC for all fuels.

Basic research on cleaner, more efficient fuels is needed for stationary generators and ICEs. Hydrogen could be a significant factor in such a transition-used either in its pure form or in combination with more conventional fuels. By blending different quantities of hydrogen, it can transition smoothly into an all-hydrogen energy system while still leveraging our existing infrastructure and technology. Taking into consideration safety, efficiency, and ecological issues, the safe, efficient, and ecologically clean operation of hydrogen-powered power generators requires further research and development related to specific features of hydrogen fuel blends combustion in stationary generators, including fuel composition, flame stability, emissions, and flexibility of operation.

In this study, a gasoline-powered laboratory test rig engine has been utilized to gather baseline data for comparison and to validate the simulation outcomes. Next, Diesel-RK software has been utilized to calculate the impact of incorporating hydrogen in gasoline at varying volume ratios (5 %, 10 %, and 15 %) on the engine's performance,

combustion features, and emissions at varying speeds. The purpose of this study is to use the diesel-RK simulation software to analyze the effects of using hydrogen on the characteristics of a single-cylinder gasoline engine numerically. In addition, this study proposes a novel approach by advocating the direct use of solar-powered PEM hydrogen generation, thereby eliminating the need for hydrogen storage. A comparison with related previous studies is presented in Table 1 to highlight the key differences, methodological gaps, and the novel contributions of this work.

2. Methodology

2.1. Hydrogen production

Proton exchange membrane (PEM) shown in Fig. 1(a) is a hydrogen generator device that uses water electrolysis to generate pure hydrogen from water with direct current (DC) energy [18]. This approach utilizes a proton-conducting polymer membrane, such as Nafion, to facilitate ion transport between the electrodes, differentiating it from other methods like alkaline electrolysis [19]. The device is available commercially in the market and was referenced in this study to reflect its typical functional characteristics. The main electrochemical reactions occurring within the PEM cell are as follows:

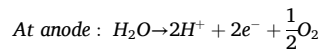
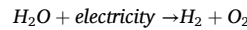


Table 1
A comparison with related previous studies.

Study	Fuel Type / Blend	Methodology	Limitations	What This Study Adds
Jayaprabakar et al. [7]	Hydrogen enrichment overview	Literature review only	No experimental or simulation data	Provides original experimental + simulation results
Ji et al. [8]	Hydrogen in DI gasoline engine	Experimental	Single injection timing; hydrogen stored in tanks	Models multiple blends; proposes direct use without storage
Erdemir et al. [17]	5 %, 10 %, and 15 % of H ₂ + gasoline, methane, propane	Experimental	Single speed test (rpm not specified); hydrogen stored in tanks	Examines wide speed range; suggests solar-powered direct hydrogen use
Al-Dawody et al. [15]	Oxy-Hydrogen with diesel	Simulation (Diesel-RK)	Diesel only; no gasoline modeling	Diesel-RK modeling for gasoline-hydrogen blends
This study	Gasoline + 5 %, 10 %, 15 % H ₂	Experimental (baseline) + Simulation (Diesel-RK)	—	Combines experiment baseline + simulation; avoids hydrogen storage by proposing on-demand generation via solar-powered PEM electrolyzers.

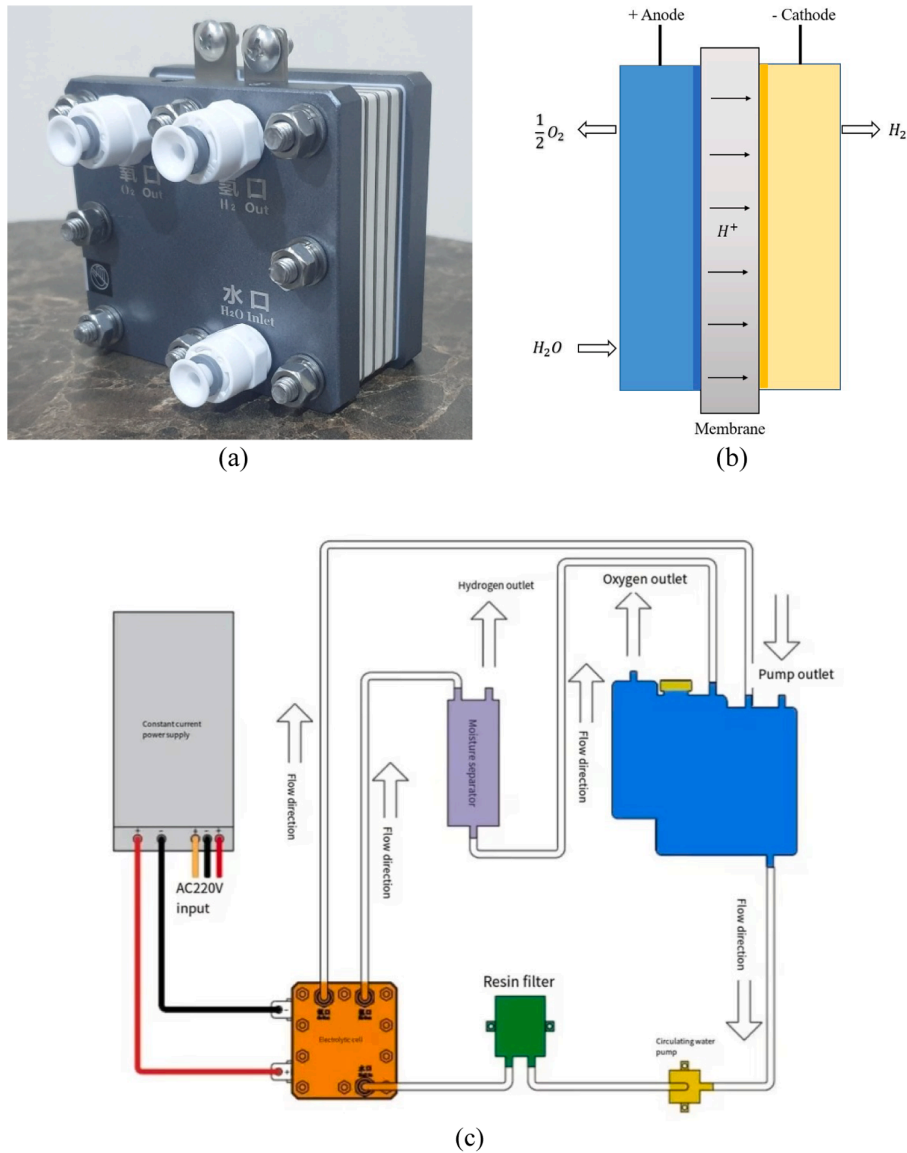
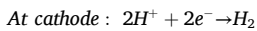


Fig. 1. Schematic diagram of the proposed PEM Hydrogen generation system.



At the anode, deionized water undergoes decomposition into hydrogen ions (H^+) and electrons (e^-), concurrently releasing oxygen gas as shown in Fig. 1 (b). The hydrogen ions traverse the membrane to the cathode, where they amalgamate with electrons to produce pure hydrogen gas. This method is exceptionally efficient and rapid to generate hydrogen with a purity level of up to 99.99 %, rendering it appropriate for applications necessitating high-quality hydrogen [20]. It functions at comparatively low temperatures, hence enhancing operational safety. The substantial expense of utilizing materials such as platinum as a catalyst, along with the restricted operational lifespan resulting from membrane degradation, presents considerable obstacles to the extensive use of this technology. Nonetheless, advancements in contemporary materials and technologies are enhancing the efficiency of these devices while decreasing their costs, rendering them a more viable alternative in clean energy generation.

Fig. 1 (c) shows the schematic of the hydrogen generator. The hydrogen generator PEM comprises a deionized water supply tank,

which consistently supplies water to the cell, preventing overheating and damage. A separator tank separates the water droplets from the H and returns these droplets to the water tank. A power supply provides the cell with DC electrical energy. The oxygen produced from this process is returned to the water tank or can be used for other purposes. It should be noted that the described hydrogen generation system, which photovoltaic panels could potentially be powered to produce hydrogen on demand without storage, was presented solely to demonstrate future feasibility, including technical and economic aspects. Accordingly, no physical experiments were conducted.

2.2. Engine test

A laboratory test rig, as shown in Fig. 2, consisting of a single-cylinder, four-stroke, air-cooled engine equipped with engine speed, torque, airflow, fuel flow, and exhaust temperature measuring devices was used in the ICEs Laboratory in the Renewable Energy Unit at the Technical Institute of Hawija, Northern Technical University. Experiments were conducted on gasoline fuel to generate baseline data for

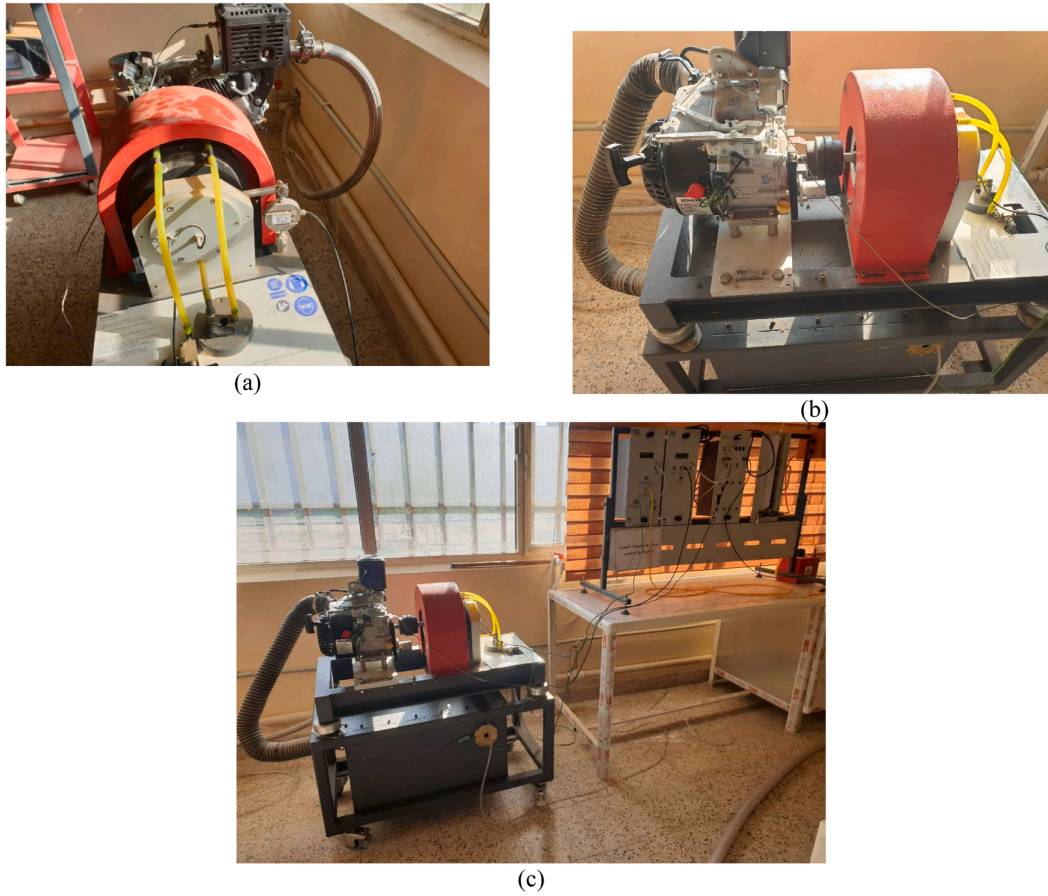


Fig. 2. Laboratory test rig used for gasoline engine experiments.

comparison and to confirm the simulation results. Subsequently, the numerical simulations were carried out using Diesel-RK software to analyse the performance, combustion characteristics, and emissions of NO_x for the same engine, fuelled by gasoline blended with hydrogen at volumetric ratios of 0 %, 5 %, 10 %, and 15 %. Table 2 presents the engine specifications. All computations were conducted under full load with a constant compression ratio and various engine speed ranges of 1400–3600 rpm. Hydrogen gas was theoretically introduced into the intake system alongside gasoline in the simulation. Table 3 enumerates the characteristics of gasoline, hydrogen, and their assigned blends used in the numerical study. The detailed equations and modeling assumptions employed in the simulation are directly adopted from the Ref. [21], which comprehensively explains the Diesel-RK methodology and internal simulation structure. In our simulation, the Wiebe combustion model was applied, ignition timing was manually adjusted per speed, and hydrogen–gasoline properties were entered into the fuel library as

Table 2
Engine specifications [22].

Parameter	Value
Engine brand	KOHLER CH270 Petrol Engine
Type of engine	Single cylinder, 4-Stroke, IC Engine
Bore x Stroke x Crank radius	70 mm x 54 mm x 27 mm
Connecting rod length	84 mm
Cylinder capacity	0.208 L
Material of piston	Iron
Compression ratio	8.5:1
Net power	4.5 kW at 3600 rpm
Airbox orifice diameter	0.0185 m

shown in Fig. 3. NO_x emissions were estimated using the Zeldovich mechanism. Fig. 4 illustrates the Diesel-RK simulation flowchart, showing input definition, simulation steps, and output extraction for performance and emissions analysis.

3. Theoretical calculations

The power output (P_{out}), which is expressed in engines by the term brake power (BP), can be calculated by [24]

$$\text{BP} = \frac{2\pi \cdot N \cdot T}{60000}$$

The mass flow rate of fuel (m_f) is determined using the following equation:

$$m_f = v \cdot \rho_f$$

To find the mass rate of air (m_a) the air flow velocity equation is modified to separate out the factors of density and to include the coefficient of discharge (C_d) for the orifice and the orifice diameter:

$$m_a = C_d \frac{\pi d^2}{4} \sqrt{\frac{2P_A \Delta P}{RT_A}}$$

The air/fuel ratio is simply the ratio of the air mass flow rate to the fuel mass flow rate:

$$\text{AFR} = \frac{m_a}{m_f}$$

Air fuel equivalence ratio (λ) is the ratio of actual AFR to ideal AFR. If

Table 3
Properties of fuels under investigation [21,23].

Properties	units	Gasoline	H ₂	95 %Gasoline + 5 % H ₂	90 %Gasoline + 10 % H ₂	85 %Gasoline + 15 % H ₂
C	%	85.5	0	81.225	76.95	72.675
H	%	14.5	100	18.775	23.05	27.325
O	%	0	0	0	0	0
Density	kg/m ³	740	0.081	703.00405	666.0081	629.01215
Heating value	MJ/kg	43.8	120	47.61	51.42	55.23
Viscosity	Pa.s	0.00029	0.000009	0.00027595	0.0002619	0.00024785
Molecular weight	kg/mole	115	2.016	109.3508	103.7016	98.0524
Fuel thermal capacity	J/kg.K	2500	14,300	3090	3680	4270
Specific vaporization heat	Kj/kg	230	0	218.5	207	195.5
Cetane number	-	0	53.2	2.66	5.32	7.98

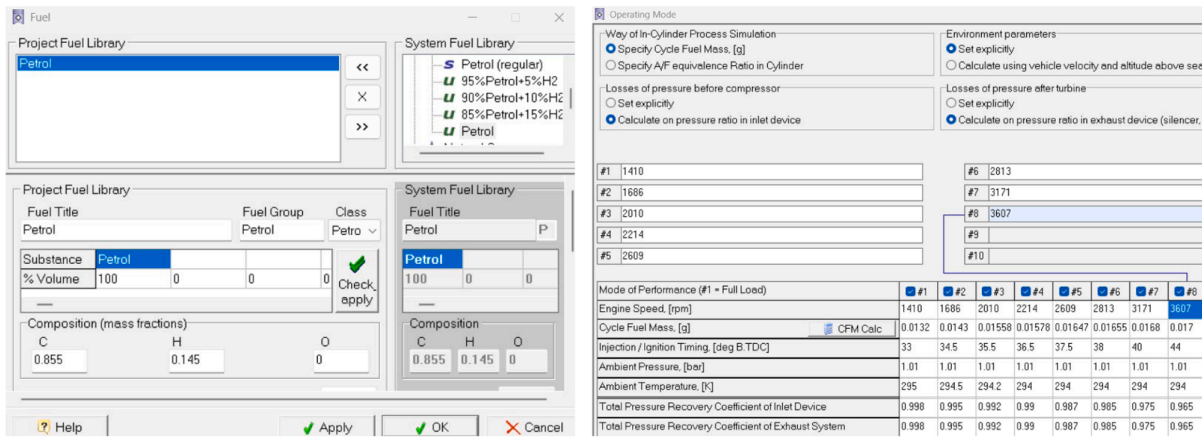


Fig. 3. Diesel-RK simulation environment used for modeling hydrogen-gasoline blends.

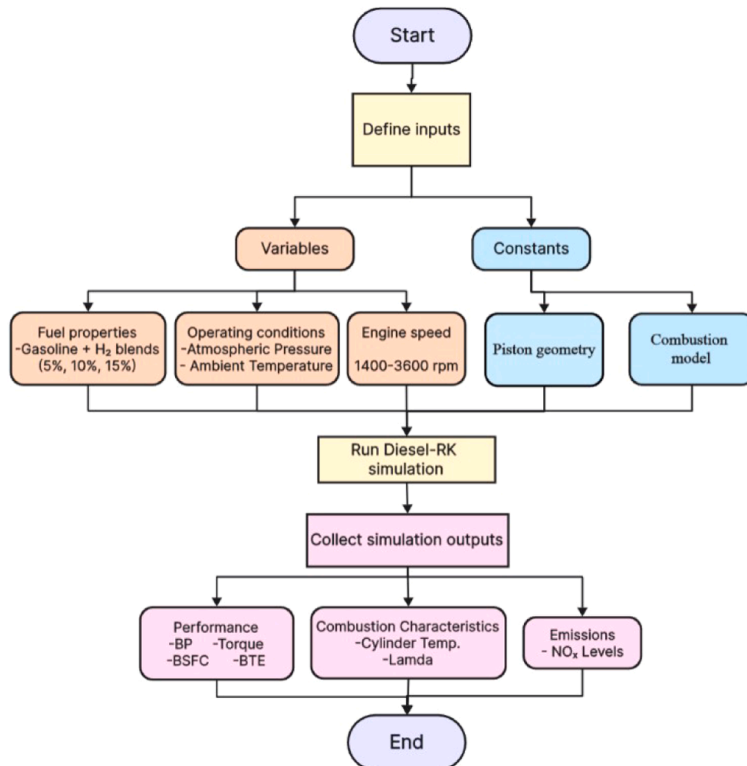


Fig. 4. Diesel-RK simulation flowchart outlining inputs, process, and outputs.

$\lambda = 1$ is ideal, $\lambda < 1$ is rich in fuel, $\lambda > 1$ rich of air

$$\lambda = \frac{AFR}{AFR_{ideal}}$$

BSFC is derived from the following equation.

$$BSFC = \frac{m_f}{BP}$$

BTE can be readily derived from the equation below.

$$BTE = \frac{BP}{m_f * LCV} * 100\%$$

Where LCV is the low calorific value of fuel.

4. Validation

This section aims to juxtapose the findings of the numerical analysis with those obtained from a laboratory engine system operating under analogous circumstances for gasoline fuel. Experimental and simulation results for each gasoline engine speed are shown in Tables 4 and 5, respectively.

Tables 4 and 5 illustrate the full load history of torque, BP, brake mean effective pressure (BMEP), BSFC, and BTE of gasoline at varying speeds. When running the simulation, the Injection /ignition timing (deg B.TDC) was changed as the engine speed changed. As the speed increased, the cycle duration decreased, which required adjusting the ignition timing so that combustion started relatively early. As engine speed increases, the inlet and outlet air velocity increases, leading to an increase in the pressure loss of the air to the combustion chamber [25]. The pressure loss coefficient was modified on this basis. The disparity between them is less than 5 %, indicating that the precision of the current research is satisfactory. Such deviation is within accepted limits in similar simulation studies [26].

5. Results and discussion

Hydrogen gas has been used as a supplementary fuel in the engine. Multiple variables include performance data, such as BP, torque, BSFC, and BTE, and combustion parameters such as maximum cylinder temperature, air-fuel equivalence ratio (λ), minimum octane number, and NO_x emissions, all visually shown at different engine speeds. It is worth noting that hydrogen has a faster flame speed and lower ignition energy compared to gasoline. This means that for every 10 % hydrogen blend, the ignition timing will generally need to be retarded three degrees compared to pure gasoline to prevent knocking and ensure proper combustion [27,28].

Fig. 5 shows the brake power of a gasoline engine with respect to engine speed using gasoline only and with different hydrogen ratios (5 %, 10 %, and 15 % vol.). It can be seen that gasoline with high hydrogen ratios achieves the highest brake power at low engine speeds compared to gasoline, and this power decreases with increasing speed. When adding 5 % hydrogen, the brake power improves slightly, maximum improve 8 % at 1686 rpm, indicating that this ratio may enhance the combustion process. However, when increasing the hydrogen ratio to 10

% and 15 %, the brake power improves by 16 % and 22 %, respectively. Then, above 2700 rpm, the brake power begins to decrease, reflecting a negative effect due to the change in the properties of the fuel mixture. This may be due to an imbalance in the air-fuel ratio despite the increase in energy density of the mixture with increasing hydrogen ratio. In general, the figure shows that adding hydrogen in small proportions may have a positive effect, while higher proportions lead to a decrease in performance.

Fig. 6 shows the relationship between engine torque (N.m) and engine speed (rpm). It can be seen from the figure that torque gradually increases with increasing engine speed until it reaches a maximum value, then begins to decrease at higher speeds. This behaviour is normal in ICEs, where the engine achieves maximum torque at a certain speed known as the optimum speed. This pattern appears in all blends, but with differences in the maximum torque values according to the percentages of added hydrogen. It is noted that adding small ratios of hydrogen to gasoline increases torque significantly at almost all speeds. The higher the ratio of hydrogen in the mixture, the higher the torque at low and medium speeds, somewhat at 1410 rpm 10 % and 15 % of hydrogen achieving 17 % and 22 %, respectively. This is explained by the fact that hydrogen improves the combustion properties thanks to its high ignition speed and high calorific value, which increases the engine's efficiency and its ability to produce higher torque. At high speeds, torque begins to gradually decrease, and the differences are clear between pure fuel and fuel with 15 % hydrogen; the decrease was 10 % at 3607, because the engine in this case does not utilize its full energy.

Fig. 7 shows the relationship between BSFC in kg/kWh and engine speed (rpm) when using only gasoline and with different hydrogen ratios added (5 %, 10 %, and 15 %). Regardless of the fuel type, it has been observed that the BSFC increases with increasing engine speed. When comparing the fuels, gasoline with only 5 % hydrogen shows the lowest BSFC across most of the engine speed range, maximum reduction was 7.5 % at 1686 rpm, indicating its relative efficiency. As the hydrogen ratio increases by 10 % and 15 %, BSFC decreases more at low and medium speeds. At 1410 rpm, 10 % and 15 % of hydrogen achieved 14.5 % and 18 % reduction, respectively. But at high speeds, BSFC increases significantly, especially with 15 % of hydrogen. This means that adding hydrogen in small amounts might help improve fuel burning. On the other hand, adding hydrogen in large amounts makes the fuel mixture less efficient and increases consumption because the fuel does not burn completely, and these results align with the findings of Ayissi et al. [11].

Fig. 8 shows the relationship between BTE and engine speed (rpm). It can be seen that the BTE of gasoline is higher at all engine speeds than that of the mixture with hydrogen. When 5 % hydrogen is added, the efficiency is close to that of gasoline but slightly lower. As the hydrogen ratio increases to 10 % and 15 %, there is a noticeable decrease in BTE, especially at higher speeds. This indicates that the combustion of the fuel mixture becomes less efficient as the hydrogen ratio increases, possibly due to an increase in the calorific value of the fuel, a change in the properties of the mixture, which may lead to a richer air-fuel ratio and incomplete combustion at high speeds. This indicates that the BTE may decrease if the energy generated by combustion is not optimally utilized. Similar findings were reported by Wang et al. [29], where higher hydrogen ratios at high speeds led to reduced BTE due to incomplete

Table 4
Experimental results.

Engine speed (rpm)	BP (W)	T (Nm)	BMEP (bar)	BSFC (kg/kWh)	BTE (%)	Ambient air tempe. (C)	Exhaust gas tempe. (C)	Airbox differential press. (Pa)
1410	1550.3	10.5	6.36	0.359913	22.83	21.8	489	-74
1686	2083.3	11.8	7.13	0.345765	23.77	21.5	505	-93
2010	2588.9	12.3	7.44	0.354743	23.17	21.1	552	-147
2214	2921.3	12.6	7.59	0.361072	22.76	21	577	-171
2609	3606.4	13.2	7.97	0.357362	22.99	20.9	605	-246
2813	3858.9	13.1	7.92	0.360098	22.82	21	610	-278
3171	4316.8	13	7.87	0.369435	22.25	21.1	631	-367
3607	4646	12.3	7.42	0.395178	20.79	20.5	654	-429

Table 5
Numerical results.

Engine speed (rpm)	BP (W)	T (Nm)	BMEP (bar)	BSFC (kg/kWh)	BTE (%)	Injection /ignition timing (deg B. TDC)	Total press. recovery coeff. of inlet & exhaust
1410	1560.9	10.572	6.3923	0.35772	22.977	33	0.998
1686	2033.3	11.517	6.9637	0.35573	23.105	34.5	0.995
2010	2638.7	12.417	7.5804	0.35504	23.085	35.5	0.992
2214	2951.9	12.747	7.6466	0.35609	23.092	36.5	0.99
2609	3580.8	13.107	7.9252	0.36001	22.831	37.5	0.987
2813	3858.3	13.099	7.92	0.36299	22.606	38	0.985
3171	4265.1	12.845	7.7667	0.37471	21.935	40	0.975
3607	4611.3	12.209	7.3822	0.39892	20.63	44	0.965

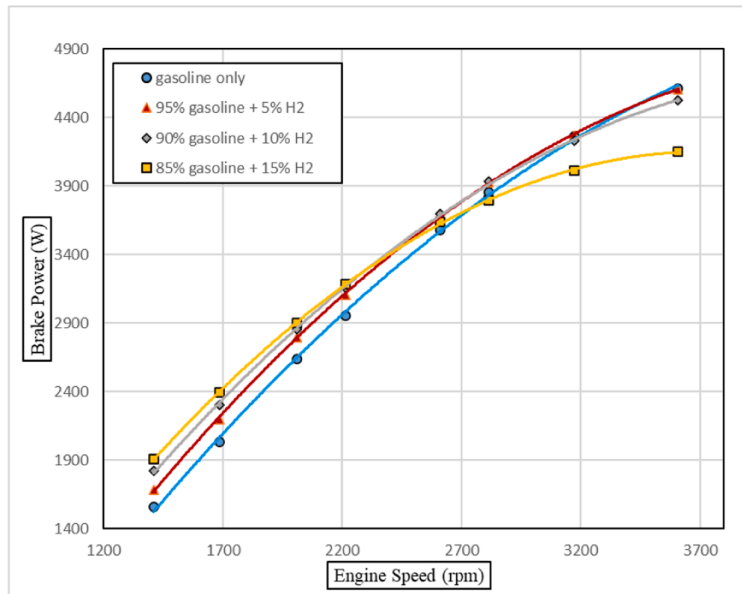


Fig. 5. BT vs. engine speed for gasoline-H₂ blends.

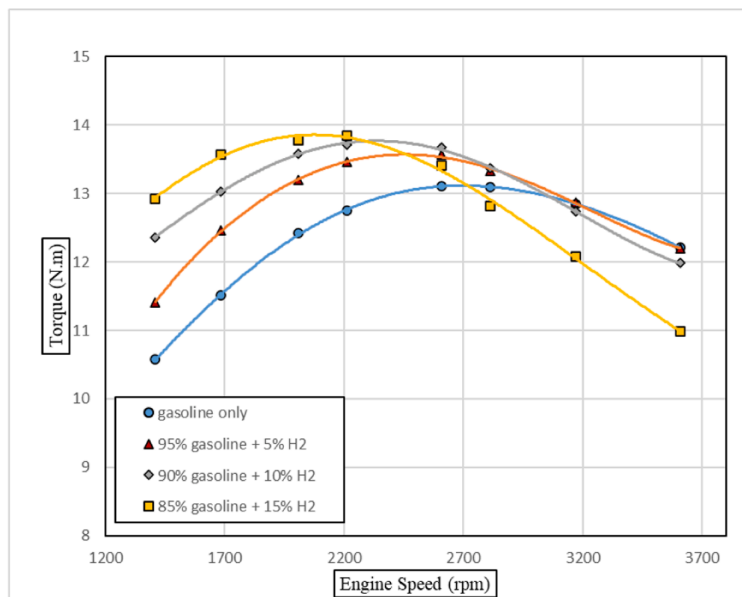


Fig. 6. Torque vs. engine speed for gasoline-H₂ blend.

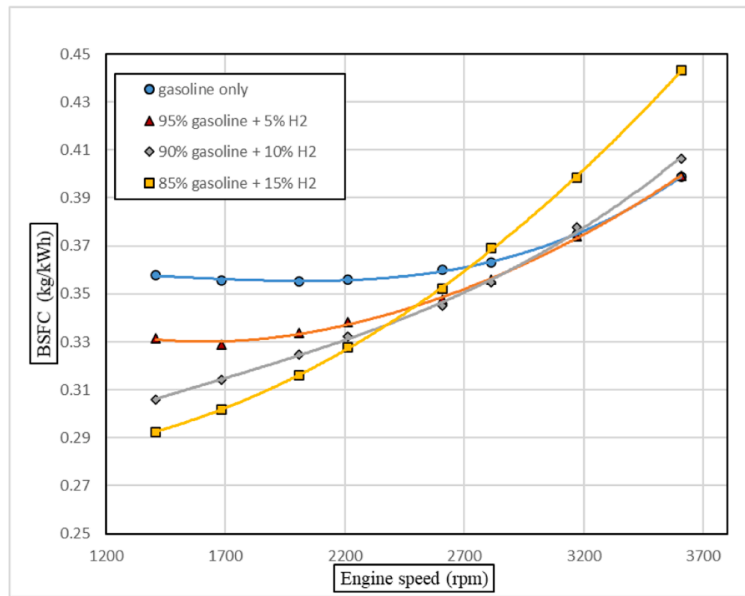


Fig. 7. BSFC vs. engine speed for gasoline-H₂ blends.

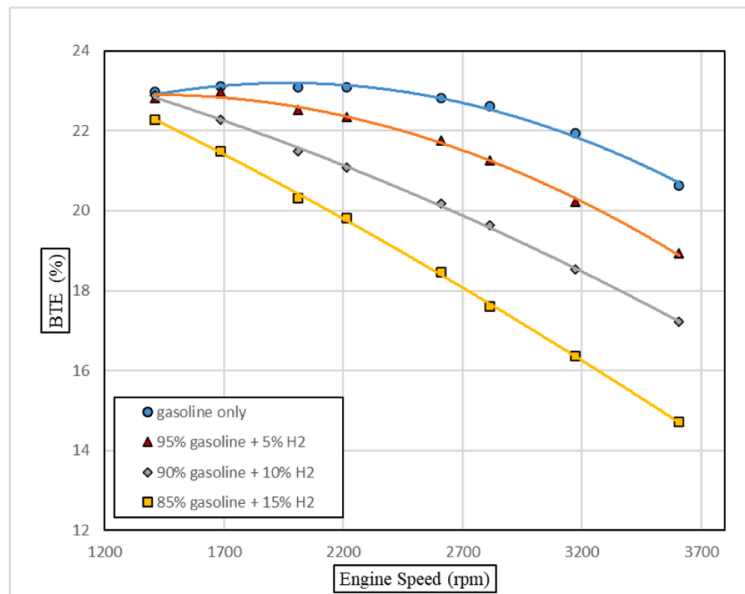


Fig. 8. BTE with engine speed for gasoline-H₂ blends.

combustion and mixture imbalance.

The combustion characteristics are studied in terms of maximum cylinder temperature, λ , and minimum octane number of fuels (knock limit). Fig. 9 shows the relationship between maximum cylinder temperature in Kelvin and engine speed. It is clear that the maximum cylinder temperature gradually decreases with increasing engine speed, regardless of the type of fuel used. This behaviour can be explained by the fact that as engine rpm increases, the combustion process becomes faster, reducing the time available for complete combustion and thus reducing the maximum temperature. For the same resin, when using gasoline with hydrogen, it has been noticed that the temperature in the cylinder is lower compared to pure gasoline. By adding 5 % hydrogen, the maximum temperature decreases slightly, and reaches its maximum,

decreasing by 3.5 % at 3607 rpm. As the hydrogen ratio increases to 10 % and 15 %, the maximum cylinder temperature continues to gradually decrease, at 3607 rpm reaches its maximum decreasing by 8 % and 14 %, respectively. This reduction is attributed to incomplete combustion at high engine speeds due to the formation of a richer air-fuel mixture, which limits oxygen availability and reduces thermal efficiency. This also results in less heat release and lower thermal stress on the engine, which aligns with trends reported in similar studies on oxygenated fuel blends [30]

Fig. 10 shows the relationship between engine speed and λ . The figure shows that the equivalence ratio starts at higher values and gradually decreases with increasing engine speed, regardless of the fuel. As the hydrogen ratio increases, the equivalence ratio decreases more

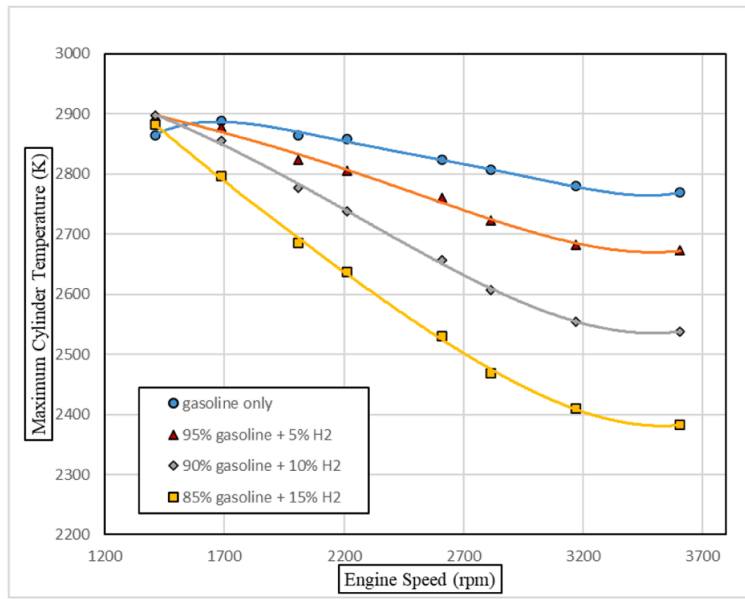


Fig. 9. Maximum cylinder temperature vs. engine speed for gasoline-H₂ blends.

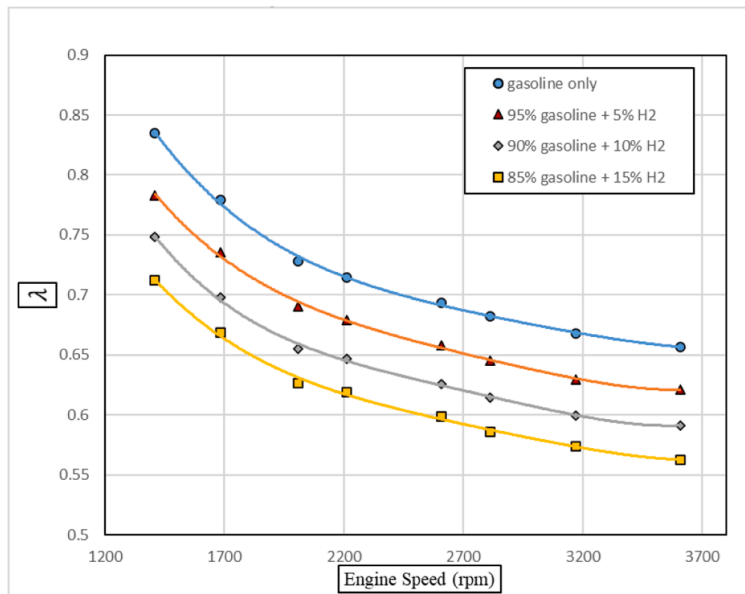


Fig. 10. Air-fuel equivalence ratio (λ) vs. engine speed.

than with gasoline alone. The effect is more pronounced at higher hydrogen ratios (e.g., 15 %). The explanation for this is that at low speeds, the equivalence ratio is higher because the engine is operating with a mixture closer to complete combustion due to the relatively high AFR. At high speeds, the equivalence ratio decreases, meaning that there is less air compared to fuel. There is no doubt that adding hydrogen improves combustion characteristics, but this requires the presence of the appropriate amount of air for combustion or raising the percentage of oxygen in the air.

The minimum octane number of a fuel is a constant property that depends on the chemical composition of the fuel and is not changed by the engine speed itself. However, conditions inside the combustion chamber, such as pressure, temperature, and ignition timing, vary with

engine speed, and this can affect the tendency for knocking to occur. Fig. 11 shows the relationship between engine speed and the minimum octane number required to prevent knocking when using gasoline only and compared to gasoline-hydrogen blends of 5 %, 10 %, and 15 %. It is clear from the figure that using gasoline only requires a higher-octane number, while with the addition of hydrogen, the required octane number gradually decreases as the proportion of hydrogen in the mixture increases, especially at high speeds. This is due to the special properties of hydrogen; it has a high ignition speed and better combustion ability, which reduces the tendency of the mixture to ignite prematurely or to cause knocking. The figure also shows that this decrease in the required octane number can vary depending on the engine speed, as different combustion conditions at different rpms affect

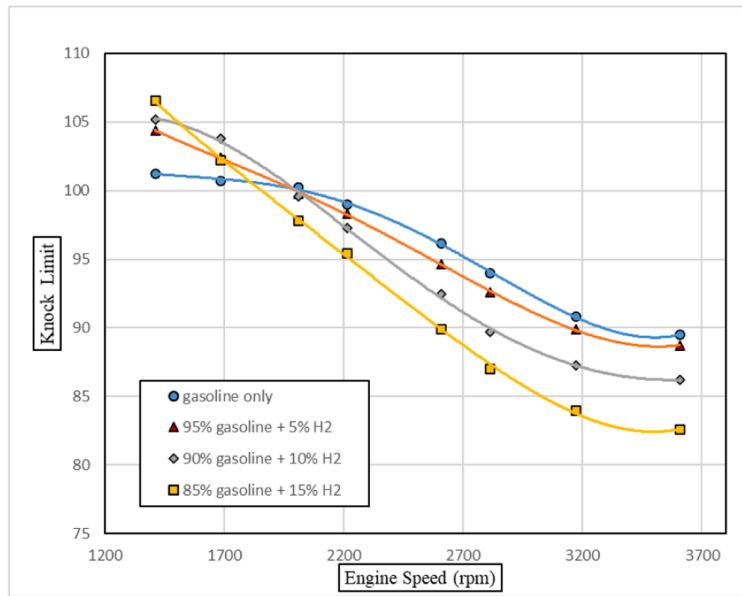


Fig. 11. Variations in Knock limit vs. engine speed for gasoline and H₂ blends.

how the engine takes advantage of the properties of hydrogen. In general, the 10 % and 15 % hydrogen ratios decrease the knock limit by 4 % and 8 %, respectively. Combining hydrogen with gasoline improves the combustion process and reduces the fuel’s requirements in terms of knocking resistance, which shows that the engine can operate more efficiently using fuel with a lower octane number.

Low NO_x emissions are often accompanied by low flame temperature and low air volume. When hydrogen gas is introduced, the amount of gasoline is reduced, resulting in a lean mixture, a lower flame temperature, and less air volume for ignition. As a result, NO_x is reduced, as shown in Fig. 12. It can be seen that NO_x emissions are highest when using gasoline only, starting at 1505 ppm at low engine speed (1410 rpm) and then gradually decreasing as engine speed increases to 145 ppm at 3607 rpm. When adding 5 % hydrogen, emissions are

significantly reduced, being around 811 ppm at 1410 rpm, and continue to decrease until they reach less than 89 ppm at 3607 rpm, an average improvement of about 40 % compared to gasoline alone.

The hydrogen content increases to 10 %; the improvement in NO_x emissions continues, with emissions starting at around 524 ppm at 1410 rpm, representing an improvement of around 65 % compared to gasoline alone, and dropping to less than 56.5 ppm at high speeds. With the addition of 15 % hydrogen, the greatest reduction in emissions is achieved, starting at around 345 ppm at 1410 rpm, representing a 77 % improvement compared to gasoline alone, and continuing to drop to less than 36 ppm at 3610 rpm. The presence of hydrogen lowers emission profiles by improving combustion characteristics due to the cleaner combustion properties of hydrogen, Similar NO_x reductions with hydrogen blends were also reported by Wang et al. [31].

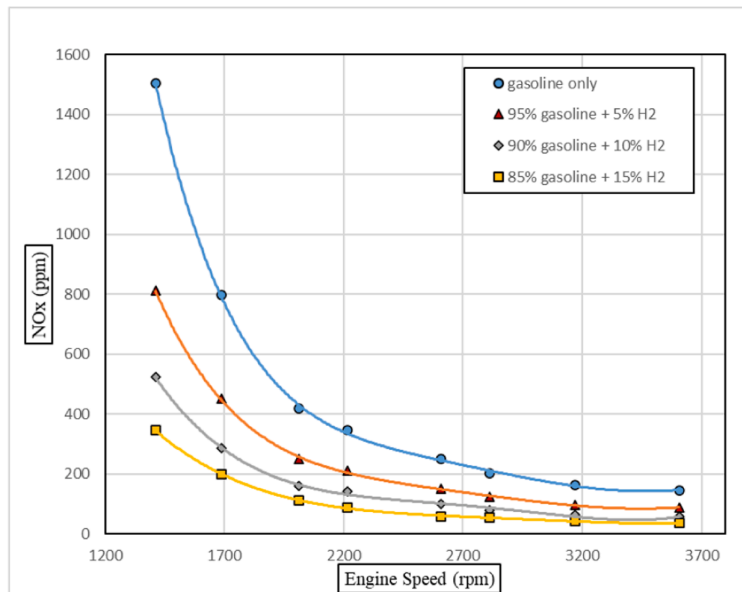


Fig. 12. Variations in NO_x emissions vs. engine speed for gasoline and H₂ blends.

6. Conclusion

The study's findings demonstrate that integrating hydrogen with gasoline in ICEs enhances combustion properties and reduces hazardous emissions, with varying impacts based on the hydrogen ratio included. The main conclusions may be encapsulated as follows:

- At 1686 rpm, 5 % hydrogen enhances BP by 8 %. Increased BP by 16 % and 22 % results in 10 % and 15 % at 1407 rpm; however, BP decreases at rpm > 2700 owing to air-fuel ratio disturbances.
- At 1410 rpm, 10 % and 15 % hydrogen increased torque by 17 % and 22 %, respectively. This resulted in significant improvements in low- and middle-speed engine performance.
- 7.5 % BSFC decrease at 5 % hydrogen at 1686 rpm, 14.5 % and 18 % at 10 % and 15 % at 1410 rpm. At high hydrogen ratios and running speeds, BSFC increased, suggesting incomplete combustion.
- With 5 % hydrogen, BTE was close to pure gasoline. However, hydrogen ratios of 10 % and 15 % reduced BTE by 5 % to 8 % at high running speeds.
- Hydrogen improved the knock limit by 4 % and 8 % with 10 % and 15 % of hydrogen, giving the fuel a better chance of burning without knocking.
- Hydrogen addition significantly decreased NO_x emissions, with 40 % reduction at 5 %, 65 % at 10 %, and 77 % at 15 % compared to pure gasoline, resulting in considerable environmental improvement.

Future work will experimentally validate the proposed hydrogen generation concept and study part-load engine behavior and economic feasibility. Current limitations include the absence of physical hydrogen injection experiments and the reliance on simulation under full-load conditions using Diesel-RK models. These will be addressed in the next phase of research.

CRedit authorship contribution statement

Ali Jasim Mohammed: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources.
Obed Majeed Ali: Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

No conflict of interest exists.

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Data availability

Data will be made available on request.

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