JURNAL AR RO'IS MANDALIKA (ARMADA)
Journal website: https://ojs.cahayamandalika.com/index.php/armada

ISSN: 2774-8499 Vol. 6 No. 3 (2026)

Research Article

Effect of Hydrogen Mass Flow Rate on Performance and Emission Characteristics of a Dual-Fuel LPG Gas Engine: Experimental and Numerical Analysis

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Abstract

Indonesia's electricity sector remains heavily dependent on fossil fuels, with gas-based generation widely used for small- and medium-scale applications. Although liquefied petroleum gas (LPG) burns cleaner than coal and diesel, LPG-fueled engines still emit carbon-based pollutants. Hydrogen enrichment is a promising transitional strategy to improve combustion and reduce emissions without major engine modifications. This study evaluates the effect of hydrogen mass flow rate on the operational characteristics of an LPG gas engine operating in dual-fuel mode using combined experiments and numerical simulation. Experiments were performed on a single-cylinder, four-stroke LPG engine–generator operated at a constant 3000 rpm under steady-state electrical loads. Hydrogen was supplied at controlled mass flow rates while LPG remained the primary fuel. Performance parameters, air–fuel ratio, operating temperatures, and exhaust emissions were measured. In parallel, in-cylinder combustion was analyzed using ANSYS Forte, supported by a mesh sensitivity study to ensure numerical reliability. Hydrogen enrichment improved performance across the investigated load range, yielding maximum increases of 12.2% in shaft power, 17.2% in torque, and 8.2% in brake mean effective pressure. Specific fuel consumption decreased by up to 13.1%, while thermal efficiency increased by up to 13.5% compared with LPG-only operation. Hydrogen-enriched operation enabled leaner combustion at equivalent loads and reduced engine and lubricant temperatures by up to 12.2% and 8.3%, respectively. Emissions decreased, with maximum reductions of 8.2% in CO and 9.4% in HC. These outcomes indicate that hydrogen primarily functions as a combustion enhancer by accelerating flame propagation and promoting more complete oxidation, supporting LPG–hydrogen dual-fuel operation as a practical pathway toward lower-carbon distributed power generation.

Keywords: Dual-fuel combustion, LPG–hydrogen engine, Hydrogen enrichment, Gas engine performance, Exhaust emissions, Combustion kinetics

INTRODUCTION

Indonesia's electricity sector remains strongly dependent on fossil energy sources, posing persistent challenges to long-term sustainability and national decarbonization objectives. According to the 2021–2030 Electricity Supply Business Plan (RUPTL), approximately 80% of planned power plants continue to rely on coal- and gas-based generation, reflecting the limited penetration of clean energy technologies. This structural dependence is reinforced by rapid growth in national energy demand, which increases at an average rate of 4.2% per year. Without an effective energy transition, such trends raise serious concerns regarding energy security and environmental degradation. In this context, Indonesia's CO_2 emissions reached approximately 220 million tons in 2020 and are projected to rise sharply to around 928 million tons by 2060 if fossil fuel dominance remains unchanged.

Gas-fired power plants represent a significant share of Indonesia's electricity infrastructure, with an installed gas-based capacity of approximately 18 GW. Although gas-based systems are commonly regarded as cleaner alternatives to coal, their cumulative contribution to greenhouse gas emissions remains substantial. Liquefied petroleum gas (LPG) is widely used in gas engines for small- and medium-scale power generation due to its relatively high energy density and cleaner combustion compared with coal and diesel fuels. Nevertheless, LPG combustion still produces carbon-based emissions, including CO_2, carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x), which limits its ability to fully align with long-term net-zero emission targets. These limitations highlight the need for cleaner combustion strategies that can be implemented within existing engine infrastructures.

Recent studies from developing regions underline the broader relevance of this challenge. Fossil-fuel-based electricity generation remains a dominant driver of CO_2 emissions in emerging economies, as demonstrated in regions such as the Yellow River Basin in China, where coal-fired power generation is closely linked to rising electricity demand and emission growth (Wu et al., 2024). Similar patterns are observed across ASEAN countries, where differences in policy commitment and renewable energy deployment result in uneven emission trajectories, despite comparable economic growth pressures (Kiwan et al., 2022; Ling et al., 2021). These findings emphasize that transitional technologies capable of reducing emissions without requiring extensive infrastructural overhaul are particularly valuable for developing countries.

Within this transitional context, gas engines—especially small-scale generator sets—are increasingly recognized as practical components of national decarbonization roadmaps. Gas engines can utilize existing fuel supply and power generation infrastructure while enabling lower emissions relative to coal-based systems, thereby supporting gradual decoupling of economic growth from carbon emissions (Wang et al., 2021; Guo et al., 2023). Moreover, the integration of gas engines with renewable energy sources has been shown to enhance energy security and reduce overall system emissions through improved operational flexibility (Manni & Mansur, 2023). These attributes position gas engines as a short- to medium-term solution during the transition toward cleaner energy systems.

From a fuel perspective, LPG has demonstrated favorable performance compared with other gaseous fuels such as compressed natural gas (CNG), liquefied natural gas (LNG), biogas, and syngas in spark-ignition engines. Experimental studies report higher brake thermal efficiency and lower specific fuel consumption for LPG relative to gasoline and several alternative gaseous fuels (Birhanu, 2022; Adeboye et al., 2025). LPG has also been shown to outperform CNG and biogas in terms of regulated emissions, particularly CO and HC, due to its cleaner combustion characteristics (Al-Amoodi et al., 2024; Şimşek & Uslu, 2024). Despite these advantages, incomplete combustion at certain operating conditions and persistent carbon emissions motivate further optimization of LPG-fueled engines.

Hydrogen has emerged as a highly promising enrichment fuel for spark-ignition engines owing to its unique combustion properties. Hydrogen exhibits a significantly higher laminar flame speed and diffusivity than conventional hydrocarbons, enabling faster flame propagation, improved mixture homogeneity, and more complete combustion (Georgescu et al., 2024; Mohsen & Al-Dawody, 2022). Its low ignition energy reduces the likelihood of misfire, while its wide flammability limits allow stable engine operation across a broad range of air–fuel ratios (Bhan, 2025). When blended with LPG, hydrogen enrichment has been reported to reduce CO emissions by up to 40%, enhance thermal efficiency, and improve combustion stability, although excessive enrichment may lead to elevated combustion temperatures and increased NO_x formation.

Several transitional strategies have been proposed to integrate hydrogen into existing fuel systems without major infrastructural modifications. Among these, fuel blending—particularly hydrogen enrichment of LPG—has demonstrated notable emission reductions while maintaining engine reliability and ignition stability (Birhanu, 2022; Khudhur, 2025). Retrofit hydrogen injection systems and gas grid blending have also been explored as means to reduce the carbon footprint of established gas infrastructure, although their practical implementation and long-term impacts continue to be investigated (Aghahasani et al., 2022; Bello & Solarin, 2021).

Despite the growing body of research on hydrogen-assisted combustion, significant knowledge gaps persist in the application of hydrogen-enriched LPG for small-scale gas engines. In particular, the influence of hydrogen mass flow rate—rather than volumetric blending ratio—on engine performance, emission characteristics, and operational stability remains insufficiently quantified. Challenges related to precise mass-flow control, combustion stability limits, and emissions trade-offs under varying load conditions are not yet fully understood (Aghahasani et al., 2022; Muhammad et al., 2021; Pukalskas et al., 2021). Addressing these gaps is essential for establishing reliable and scalable dual-fuel strategies.

Accordingly, this research investigates the effect of hydrogen mass flow rate on the operational characterization of LPG gas engines operating in dual-fuel mode. The study focuses on engine performance, emission behavior, and operating conditions under steady-state operation. By providing quantitative, mass-based insights into hydrogen enrichment effects, this work aims to support dual-fuel LPG–hydrogen technology as a practical transitional pathway toward lower-carbon power generation and to contribute experimental and analytical evidence relevant to renewable energy engineering and gas engine optimization.

2. METHOD

Research Design and Approach

This study adopted an integrated experimental and numerical methodology to characterize the operational behavior of an LPG gas engine operating in dual-fuel LPG–hydrogen mode. The primary objective was to quantify the influence of hydrogen mass flow rate on engine performance, exhaust emissions, and operating conditions under steady-state operation. The experimental campaign was designed following recommended protocols for dual-fuel engine characterization, emphasizing controlled load mapping, repeatability, and measurement reliability (Lanotte et al., 2021; Cheng et al., 2022).

Experimental investigations were complemented by numerical simulations to provide insight into in-cylinder combustion phenomena that cannot be directly measured. Computational fluid dynamics (CFD) simulations were conducted using ANSYS Forte to model combustion processes, while Aspen HYSYS was employed for thermodynamic validation and fuel property consistency. This combined approach ensured that experimental observations were supported by physically consistent combustion modeling, in line with best practices reported in the literature (Laget et al., 2023; Piano et al., 2024).

2.2 Experimental Setup and Test Engine

The experimental object was a single-cylinder, four-stroke LPG engine-generator set operated at a constant rotational speed of 3000 rpm. The engine was coupled to an electrical generator and tested under a range of electrical load conditions to represent realistic small-scale power generation scenarios. During all experiments, engine speed was maintained constant to isolate the effects of hydrogen enrichment and load variation on performance and emissions.

The original fuel system was modified to allow controlled hydrogen injection while retaining LPG as the primary fuel. Hydrogen was supplied externally and introduced into the intake system at predetermined mass flow rates. This configuration enabled systematic variation of hydrogen input without altering the engine's basic mechanical design, ensuring comparability with conventional LPG operation.

Table 2.1. Specifications of the LPG Engine-Generator Set

Parameter	Specification
Brand / Model	Green Power CC5000-LPG
Rated Power	4,800 W

Parameter	Specification
Frequency	50 Hz
Generator Mode	Single-phase or Three-phase
Number of Cylinders	1
Displacement Volume	389 cc
Bore × Stroke	88 mm × 64 mm
Fuel Type	LPG
LPG Consumption	0.32 kg/kWh (rated power)
LPG Supply Pressure	2.5–3.2 kPa (25–32 mbar)
Starting System	Electric starter
Cooling System	Natural air cooling
Engine Speed	3000 rpm
Rotation Direction	Counter-clockwise (CCW)

Figure 2.1. LPG engine-generator set used in the experimental study (placeholder).

2.3 Instrumentation and Measurement Devices

Electrical output parameters, including voltage and current, were measured using a calibrated voltmeter and clamp ammeter to determine generator load and electrical power output. Fuel supply pressure was monitored using pressure regulators and gauges to ensure stable delivery conditions throughout testing.

Engine rotational speed was verified using a digital stroboscope. Exhaust emissions were quantified using a multi-gas exhaust gas analyzer capable of measuring carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), oxygen (O_2), and nitrogen oxides (NOx). Engine and lubricant temperatures were monitored using digital thermocouples positioned at critical locations. The selected instrumentation and measurement approach are consistent with established practices for hydrogen-assisted combustion studies (Ukpaukure et al., 2023; Giacomazzi et al., 2023).

Table 2.2. Pressure Regulator Specifications

Parameter	Specification
Type	550L
Maximum Inlet Pressure	16 kg/cm²
Maximum Outlet Pressure	1.5 kg/cm²

Figure 2.2. Pressure regulator with inlet and outlet gauges (placeholder).

Table 2.3. Stroboscope Specifications

Parameter	Specification
Brand	CZ SINCRO
Model	DG-85
Measurement Range	0–99,999 rpm
Accuracy	±1 digit
Measurement System	Digital

Figure 2.3. Digital stroboscope for engine speed measurement (placeholder).

Table 2.4. Exhaust Gas Analyzer Specifications

Parameter	Specification
Brand	Stargas 898
Weight	7.5 kg

Parameter	Specification
Operating Temperature	40–45 °C
Dimensions	470 × 230 × 220 mm
CO Range	0–15 % vol
CO_2 Range	0–20 % vol
HC Range	0–30,000 ppm vol
O_2 Range	0–25 % vol
NOx Range	0–5,000 ppm vol

Figure 2.4. Exhaust gas analyzer used for emission measurements (placeholder).

2.4 Experimental Variables and Fuel Properties

All experiments were conducted at a constant engine speed of 3000 rpm, while the electrical load was varied from 500 W to 5000 W in increments of 500 W. Hydrogen mass flow rate was systematically varied, while LPG and intake air flow rates were measured concurrently to capture changes in mixture composition and combustion behavior.

Measured outputs included LPG mass flow rate, air mass flow rate, electrical voltage and current, exhaust gas concentrations (CO and HC), and operating temperatures. From these measurements, engine performance indicators such as power output, torque, brake mean effective pressure (BMEP), specific fuel consumption (SFC), thermal efficiency, and air–fuel ratio (AFR) were calculated using standard engine performance equations (Paykani, 2021).

Table 2.5. Experimental Design and Variables

Category	Parameter
Constant	Engine speed: 3000 rpm; LPG engine-generator 5 kW
Fuel Types	LPG (Propane C_3H_8, Butane C_4H_{10}); Hydrogen (≥99.9% purity)

Category	Parameter
Hydrogen Mass Flow Rate	0; 0.031; 0.061; 0.092; 0.123 kg/kWh
Load Variation	500–5000 W (500 W intervals)
Measured Outputs	LPG flow; air flow; voltage; current; CO; HC; temperatures
Calculated Outputs	Power; torque; BMEP; SFC; thermal efficiency; AFR

Table 2.6. LPG Fuel Specifications

Property	Value
Main Components	Propane (C_3H_8), Butane (C_4H_{10})
Storage Pressure	760–1030 kPa
Typical AFR	15.6:1
Octane Number	~105

Table 2.7. Hydrogen Fuel Specifications

Property	Value
Purity	≥99.9%
Physical State	Gas
Combustion Product	H_2O (water vapor)

2.5 Data Processing and Numerical Analysis

Experimental data were processed to calculate engine performance parameters using established thermodynamic and engine analysis formulations. Electrical power measurements were converted into mechanical performance indicators, while fuel mass flow data were used to determine energy input, SFC, and thermal efficiency. Air–fuel ratio was calculated based on measured air and fuel flow rates.

Numerical simulations were conducted using ANSYS Forte to model in-cylinder combustion from intake valve closing (IVC) to exhaust valve opening (EVO). Detailed chemical kinetics were employed to capture the effects of hydrogen enrichment on flame propagation and heat release, following approaches reported in previous hydrogen-enriched combustion studies (Maio et al., 2022; Ugliano et al., 2024). Mesh sensitivity analysis was performed to balance numerical accuracy and computational efficiency, ensuring reliable prediction of pressure traces and temperature fields. Simulation results were validated against experimental performance and emission data to ensure consistency between numerical and experimental findings.

3. RESULT AND DISCUSSION

3.1 Numerical Simulation Results (ANSYS Forte)

Numerical simulations were conducted to investigate the in-cylinder combustion behavior of the LPG–hydrogen dual-fuel engine using ANSYS Forte. The computational domain covered the crank angle range from −180° crank angle (CA), corresponding to intake valve closing (IVC), to +180° CA, corresponding to exhaust valve opening (EVO). To reduce computational cost while maintaining acceptable accuracy, only one-eighth of the combustion chamber was simulated, applying geometric symmetry assumptions that have been validated in prior CFD studies of spark-ignition engines (Maio et al., 2022; Laget et al., 2023).

Initial conditions at IVC were set at 1 bar pressure and 360 K temperature. The air–fuel mixture consisted of LPG, modeled as a blend of 30% propane (C_3H_8) and 70% butane (C_4H_{10}), with varying hydrogen fractions introduced according to the experimental test matrix. These conditions were selected to ensure consistency between experimental and numerical analyses.

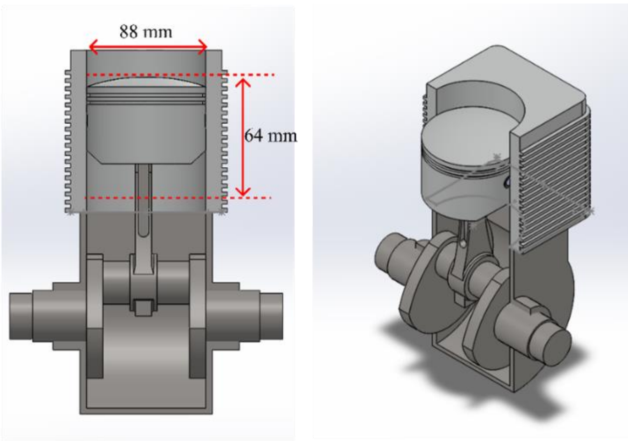

Figure 3.1. Combustion chamber geometry modeled in ANSYS Forte (placeholder).

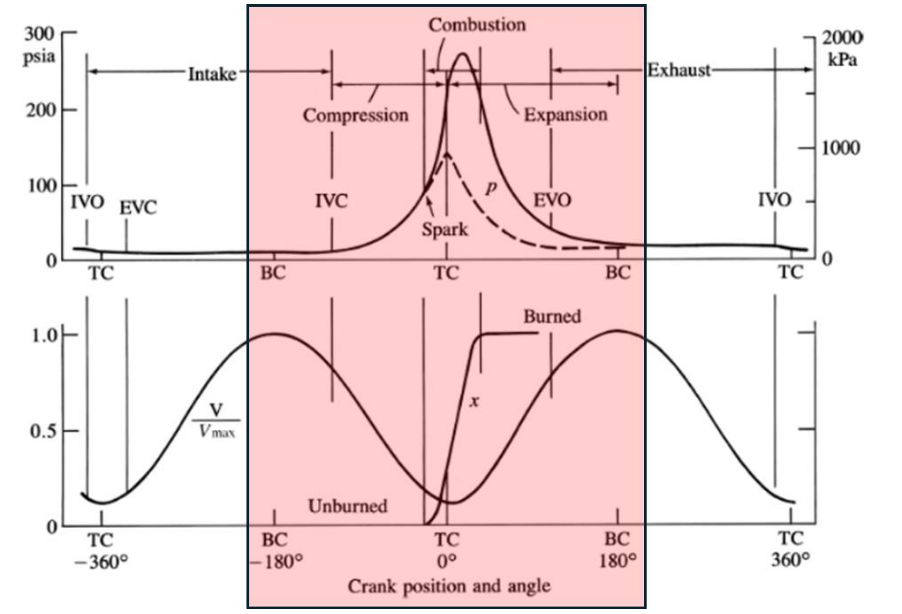

Figure 3.2. Simulation domain from intake valve closing (IVC) to exhaust valve opening (EVO) (placeholder).

A mesh sensitivity analysis was performed to ensure numerical accuracy while minimizing computational expense. The criterion for mesh selection was the deviation between simulated brake thermal efficiency (BTE) and the reference experimental BTE value of 19.16%. Five mesh configurations with increasing cell counts were evaluated.

Table 3.1. Mesh Sensitivity Test Results

Number of Cells	Thermal Efficiency (%)	Brake Thermal Efficiency (%)	Error vs. Reference (%)
7,072	24.69	14.83	22.55
12,294	25.50	14.54	24.06
17,619	17.85	11.62	39.33
26,736	20.00	12.44	35.05
55,800	30.18	18.62	2.81

Among the tested configurations, the mesh consisting of 55,800 cells exhibited the lowest deviation from the experimental reference, with an error of 2.81%. Consequently, this mesh resolution was selected for all subsequent numerical simulations, ensuring a balance between prediction accuracy and computational efficiency.

3.2 Experimental Performance Results

Experimental tests were conducted under steady-state operation at a constant engine speed of 3000 rpm, with electrical loads varied from 500 W to 4500 W. Hydrogen mass flow rate was systematically increased while maintaining LPG as the primary fuel, enabling direct comparison between LPG-only and LPG–hydrogen dual-fuel operation.

3.2.1 Shaft Power

Shaft power increased monotonically with electrical load for all fuel configurations. For hydrogen-enriched operation, shaft power consistently exceeded that of LPG-only operation across the entire load range. The maximum improvement in shaft power reached approximately 12.2%, indicating enhanced combustion effectiveness due to hydrogen addition. Similar trends have been reported in previous studies, where hydrogen enrichment improved power output by accelerating flame propagation and improving combustion completeness (Ortiz-Imedio et al., 2022; Guleria et al., 2021).

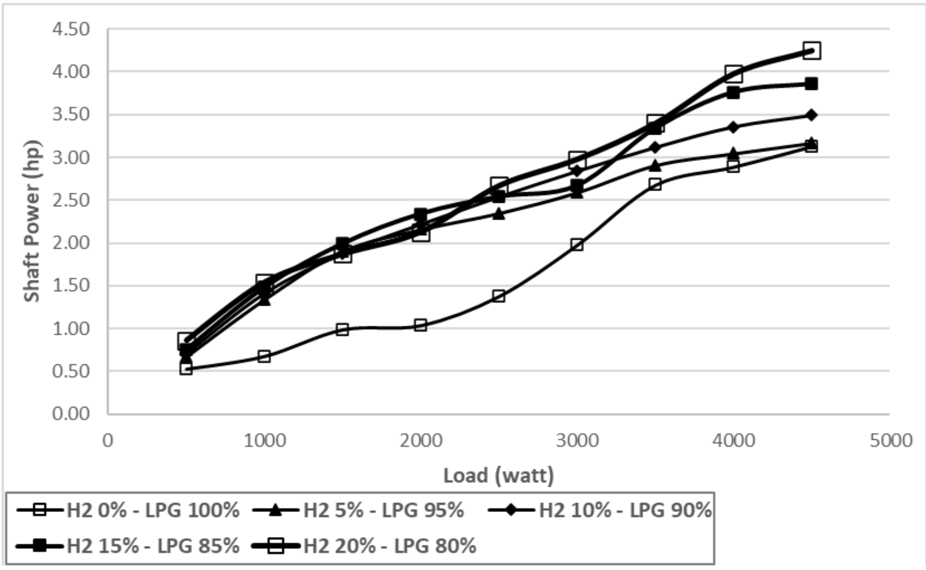

Figure 3.3. Shaft power versus electrical load for different hydrogen mass flow rates (placeholder).

3.2.2 Torque

Engine torque exhibited trends comparable to shaft power, increasing with both load and hydrogen enrichment. The enhanced torque output is attributed to higher in-cylinder pressures resulting from improved combustion kinetics. A maximum torque increase of approximately 17.2% was observed under hydrogen-enriched conditions relative to LPG-only operation, consistent with findings reported by Pal et al. (2021) and Stipić et al. (2023).

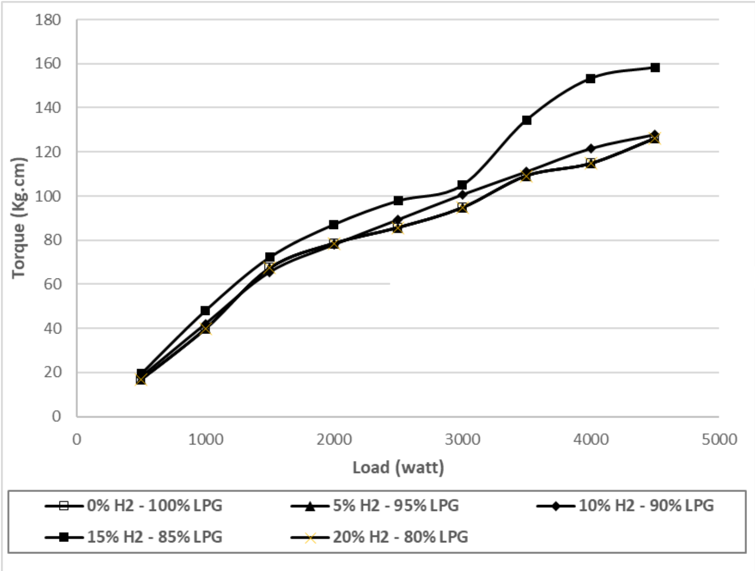

Figure 3.4. Torque versus electrical load for LPG and LPG–hydrogen operation (placeholder).

3.2.3 Brake Mean Effective Pressure (BMEP)

Brake mean effective pressure increased with rising electrical load for all test conditions. Hydrogen enrichment further elevated BMEP values, reflecting higher effective pressure during the power stroke. The maximum improvement in BMEP reached approximately 8.2% compared with baseline LPG operation. This behavior aligns with literature reports indicating that hydrogen addition enhances pressure development through faster and more complete combustion (Pal et al., 2021; Stipić et al., 2023).

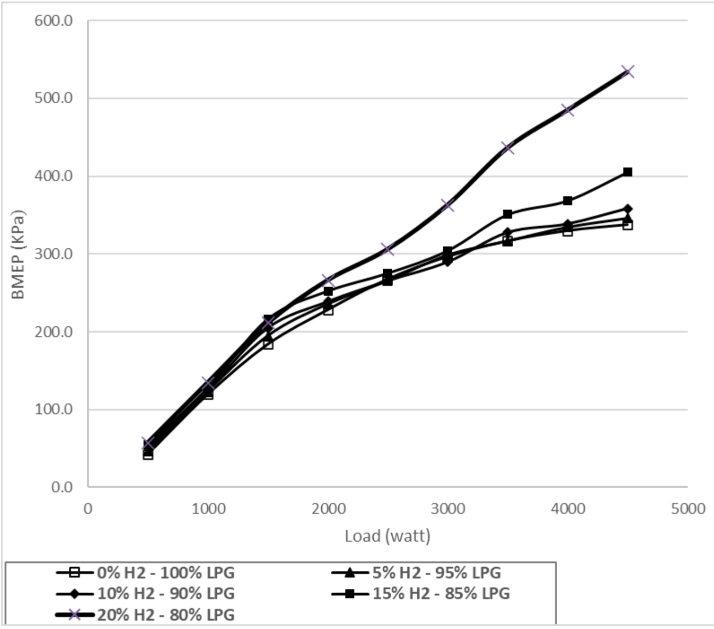

Figure 3.5. BMEP versus electrical load for varying hydrogen mass flow rates (placeholder).

3.2.4 Specific Fuel Consumption (SFC)

Specific fuel consumption decreased with increasing load for all fuel configurations, reflecting improved engine efficiency at higher loads. Hydrogen enrichment resulted in a notable reduction in SFC across the load range, with a maximum decrease of approximately 13.1% compared with LPG-only operation. This reduction is attributed to improved combustion efficiency and enhanced energy utilization, in agreement with trends reported by Zheng et al. (2021) and Gianetti et al. (2023).

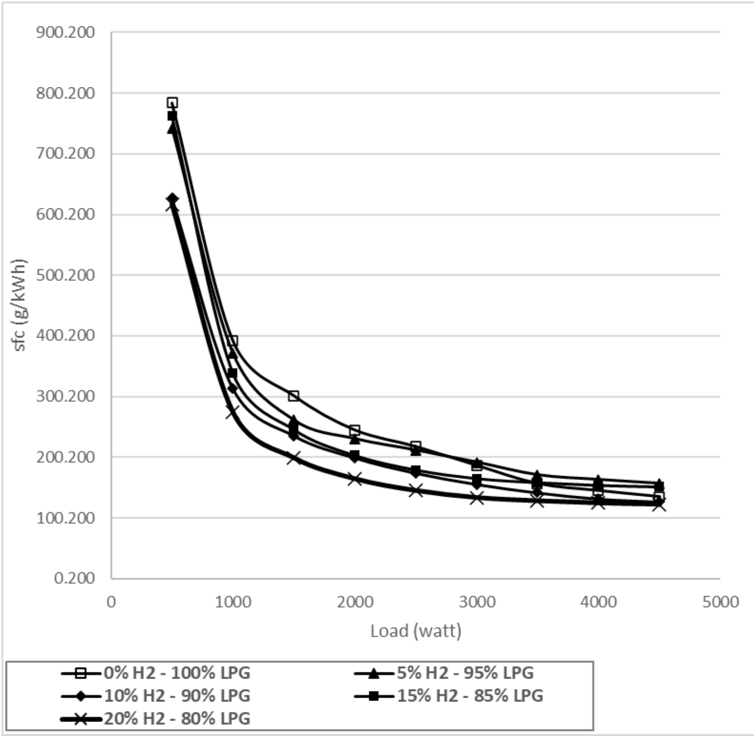

Figure 3.6. Specific fuel consumption versus electrical load under different fuel mixtures (placeholder).

3.2.5 Thermal Efficiency

Thermal efficiency increased with electrical load and hydrogen mass flow rate. The highest improvement in thermal efficiency reached approximately 13.5% relative to pure LPG operation. Enhanced thermal efficiency under hydrogen-enriched conditions is associated with faster flame development and reduced heat losses, as also reported in previous hydrogen-assisted combustion studies (Ozkara & Gül, 2025; Gianetti et al., 2023).

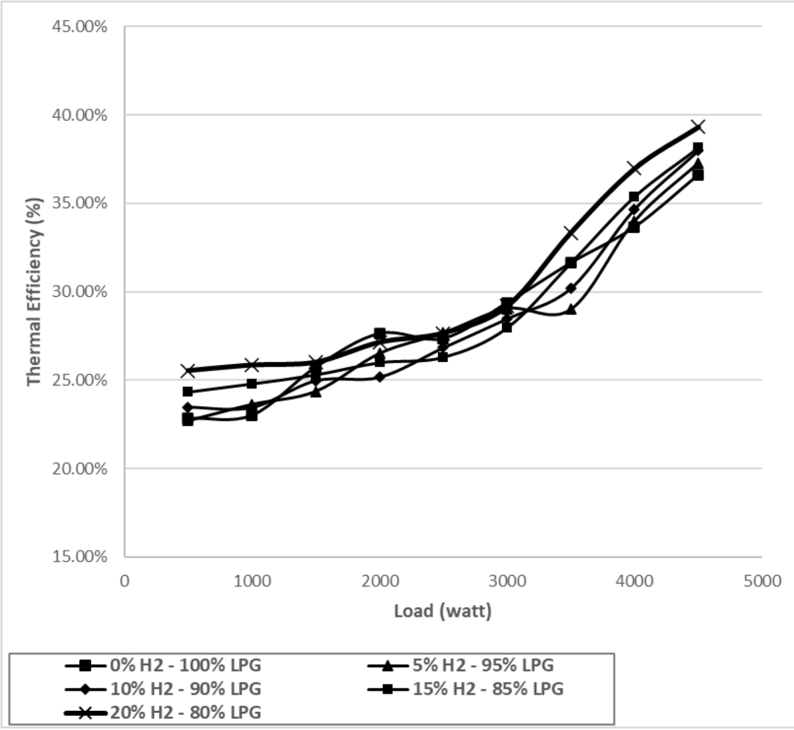

Figure 3.7. Thermal efficiency versus electrical load for LPG–hydrogen mixtures (placeholder).

3.3 Air–Fuel Ratio and Operating Conditions

3.3.1 Air–Fuel Ratio (AFR)

The air–fuel ratio decreased with increasing electrical load due to higher fuel flow requirements at elevated power outputs. At equivalent loads, hydrogen-enriched mixtures exhibited higher AFR values than LPG-only operation, indicating the potential for leaner combustion conditions enabled by hydrogen addition. This behavior supports previous findings that hydrogen enrichment expands the lean operating limit of spark-ignition engines (Jeong, 2024; Deng et al., 2025).

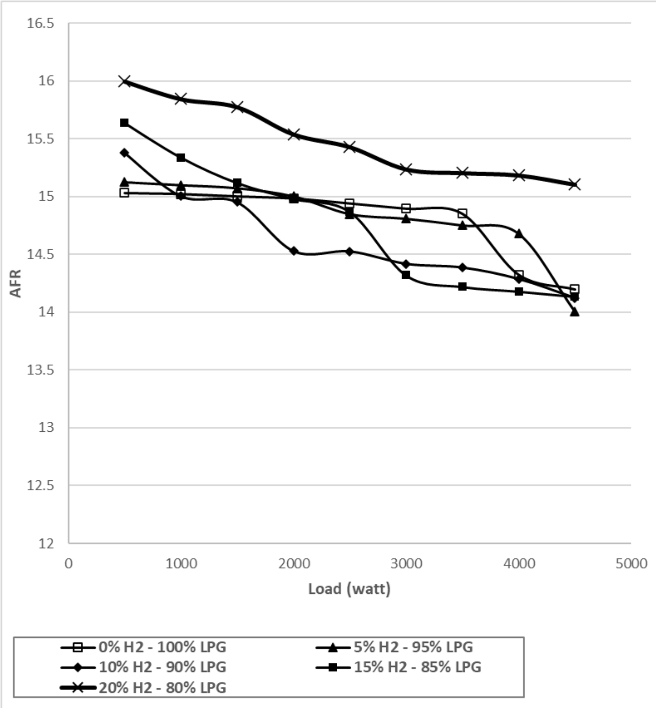

Figure 3.8. Air–fuel ratio versus electrical load for different hydrogen mass flow rates (placeholder).

3.3.2 Engine, Lubricant, and Exhaust Temperatures

Engine and lubricant temperatures increased with electrical load under all operating conditions. However, hydrogen enrichment led to a reduction in both engine and lubricant temperatures at comparable loads. Maximum reductions of approximately 12.2% in engine temperature and 8.3% in lubricant temperature were observed, suggesting more uniform heat release and reduced localized thermal stress under hydrogen-enriched combustion.

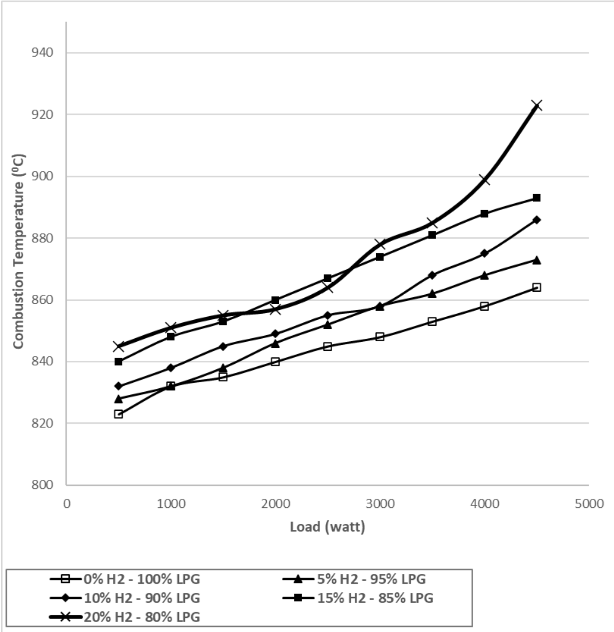

Figure 3.9. Engine and lubricant temperatures versus electrical load (placeholder).

3.4 Emission Characteristics

3.4.1 Carbon Monoxide (CO)

Carbon monoxide emissions increased with electrical load due to higher fuel input and reduced excess air availability. Nevertheless, hydrogen enrichment significantly reduced CO emissions across all load conditions. The maximum reduction in CO emissions reached approximately 8.2% compared with LPG-only operation. This reduction is attributed to improved oxidation of carbon-containing species facilitated by hydrogen's high flame speed and low ignition energy (Pandey et al., 2023; Mohamed et al., 2024).

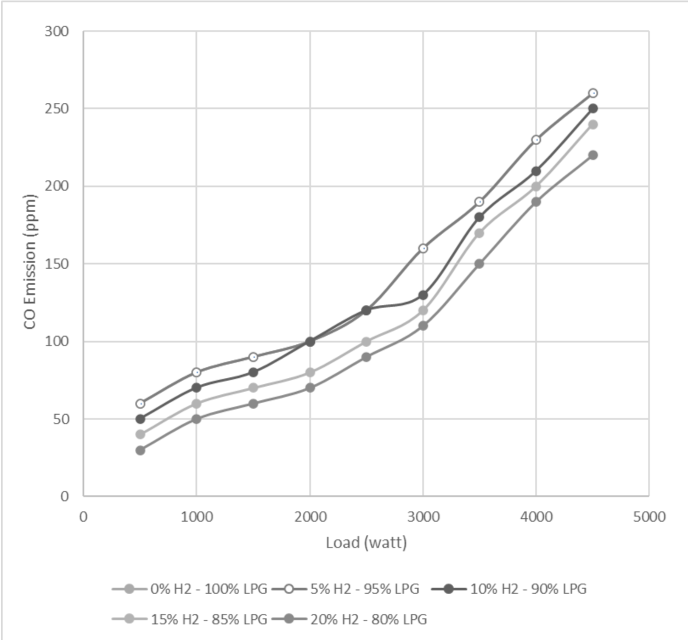

Figure 3.10. CO emissions versus electrical load for LPG and LPG–hydrogen fuels (placeholder).

3.4.2 Hydrocarbon (HC)

Hydrocarbon emissions decreased with increasing load and hydrogen mass flow rate. Hydrogen-enriched operation achieved reductions in HC emissions of up to 9.4% relative to LPG-only conditions. The observed decrease is associated with reduced flame quenching near combustion chamber walls and shorter burn durations under hydrogen-assisted combustion, as reported in previous studies (Beccari & Pipitone, 2021; Mohamed et al., 2024).

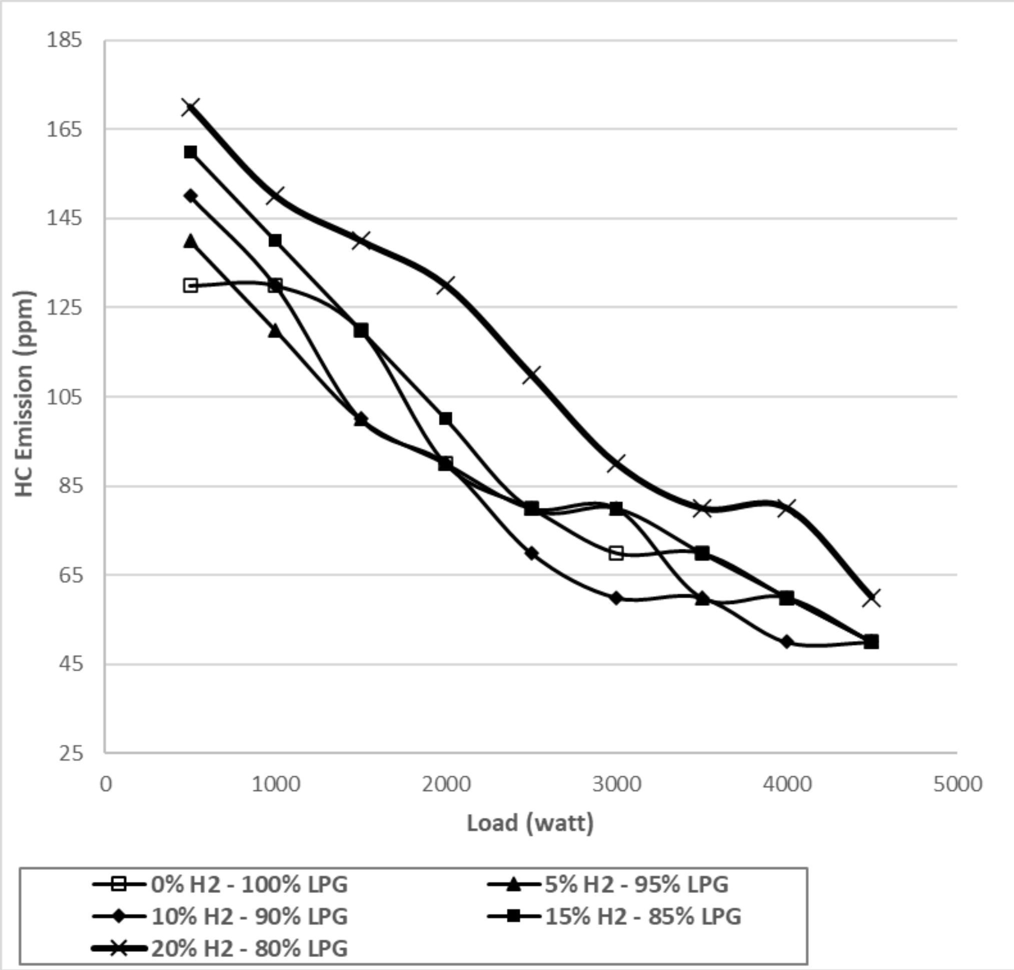

Figure 3.11. HC emissions versus electrical load under different hydrogen mass flow rates (placeholder).

Discussion

4.1 Effect of Hydrogen Enrichment on Engine Performance

The results demonstrate that hydrogen enrichment consistently enhances the performance of LPG-fueled gas engines across all tested loads. Increases in shaft power (up to approximately 12.2%), torque (around 17.2%), and brake mean effective pressure (BMEP) (about 8.2%) clearly indicate that hydrogen acts as an effective combustion enhancer rather than merely an auxiliary energy source. These improvements can be primarily attributed to hydrogen's high laminar flame speed and diffusivity, which accelerate flame propagation and promote faster and more complete combustion. As a result, peak in-cylinder pressure is shifted closer to the optimum crank angle, improving the conversion of chemical energy into mechanical work.

From a combustion kinetics perspective, hydrogen exhibits lower activation energy and higher reactivity compared with hydrocarbon fuels, enabling rapid initiation and propagation of combustion reactions. This behavior has been widely reported in hydrogen-enriched spark-ignition engines, where faster heat release rates lead to higher torque and power output, particularly under medium-to-high load conditions (Kalvakala et al., 2024; Stipić et al., 2023). The observed performance trends in this study are therefore consistent with prior experimental and numerical investigations, reinforcing the role of hydrogen as a combustion accelerator in LPG engines.

4.2 Thermal Efficiency and Fuel Consumption Characteristics

The reduction in specific fuel consumption (up to approximately 13.1%) and the corresponding increase in thermal efficiency (around 13.5%) further confirm the beneficial impact of hydrogen enrichment on engine efficiency. Improved combustion completeness reduces unburned fuel losses and enhances the effective utilization of the supplied fuel energy. Hydrogen-assisted combustion also shortens combustion duration, which limits heat losses to the cylinder walls and increases the fraction of released energy converted into useful work.

These findings align with studies reporting that hydrogen enrichment improves thermal efficiency by advancing heat release phasing and stabilizing combustion, particularly in operating regimes where LPG-only combustion is kinetically constrained (Zhou et al., 2021; Ozkara & Gül, 2025). However, the efficiency benefits are not expected to increase indefinitely with hydrogen addition. Excessive hydrogen enrichment may lead to overly lean mixtures or abnormal combustion behavior, which can offset efficiency gains if not properly controlled (Biondo et al., 2022).

4.3 Air–Fuel Ratio and Operating Temperature Behavior

The air–fuel ratio (AFR) results indicate that hydrogen-enriched operation enables comparatively leaner combustion at equivalent loads without compromising power output. This expansion of the stable operating window is a direct consequence of hydrogen's wide flammability limits and enhanced flame stability. Leaner operation contributes to improved efficiency and reduced carbon-based emissions while maintaining acceptable engine performance.

Interestingly, although hydrogen intensifies the combustion process, measured engine and lubricant temperatures decreased by approximately 12.2% and 8.3%, respectively. This behavior suggests that hydrogen enrichment promotes more uniform heat release and reduces localized hot spots within the combustion chamber. Improved flame propagation and shorter combustion duration limit prolonged exposure of engine components to high temperatures, thereby reducing thermal stress. Similar temperature reduction trends under hydrogen-enriched conditions have been reported in previous studies, particularly for small-scale engines with limited cooling capacity (Halewadimath et al., 2023).

4.4 Emission Reduction Mechanisms for CO and HC

Hydrogen enrichment resulted in notable reductions in carbon monoxide (CO) and hydrocarbon (HC) emissions, with maximum decreases of approximately 8.2% and 9.4%, respectively. These reductions can be explained by several complementary mechanisms. First, hydrogen enhances oxidation of intermediate species by increasing flame temperature and reaction rates, leading to more complete conversion of carbon-containing compounds into CO_2. Second, faster flame propagation reduces the extent of flame quenching near combustion chamber walls and crevice volumes, where unburned hydrocarbons typically originate.

The improved oxidation and reduced quenching effects observed in this study are consistent with established combustion theories and experimental findings in hydrogen-enriched SI engines (Beccari & Pipitone, 2021; Mohamed et al., 2024; Pandey et al., 2023). Collectively, these mechanisms explain the simultaneous improvement in efficiency and reduction in CO and HC emissions achieved through hydrogen enrichment.

4.5 Trade-Offs, NOx Considerations, and Optimal Enrichment Window

While hydrogen enrichment provides clear performance and emission benefits, hydrogen mass flow rate emerges as a critical control parameter. Increasing hydrogen content can elevate peak combustion temperatures, potentially leading to increased nitrogen oxides (NOx) formation, particularly at high loads and near-stoichiometric conditions. Although NOx emissions were not the primary focus of the present analysis, extensive literature indicates that hydrogen-assisted combustion often requires mitigation strategies to manage NOx formation (Rajak et al., 2021; Ortiz-Imedio et al., 2022).

Defining an optimal hydrogen enrichment window is therefore essential. Previous studies suggest that moderate enrichment levels—typically around 20–30% hydrogen by volume—offer the best compromise between efficiency improvement, CO/HC reduction, and NOx control (Biondo et al., 2022; Stipić et al., 2023). Mitigation strategies such as exhaust gas recirculation (EGR), ignition timing retardation, and lean operation can further suppress NOx formation while preserving the benefits of hydrogen enrichment.

4.6 Consistency with Literature and Practical Implications

The trends observed in this study are consistent with prior experimental and numerical investigations of hydrogen-enriched LPG and other hydrocarbon-fueled engines. Variations reported across different studies can largely be attributed to differences in engine size, compression ratio, load range, and hydrogen mixing strategy (Bhowmik et al., 2021; Nguyen & Le, 2022; Hadjkacem et al., 2023). Small-scale engines, such as the one investigated here, often exhibit pronounced responses to hydrogen enrichment due to their lower thermal inertia and simpler combustion systems.

From a practical standpoint, the combined improvements in performance and reductions in carbon-based emissions demonstrate that dual-fuel LPG–hydrogen operation represents an effective transitional strategy for distributed power generation. Importantly, these benefits are achieved without major engine hardware modifications, enhancing the feasibility of near-term implementation. Nevertheless, issues related to hydrogen safety, fuel logistics, and cost remain critical considerations for large-scale deployment (Cai et al., 2023; Devarajan et al., 2021).

Overall, the findings reinforce the concept of hydrogen as a combustion enhancer rather than a direct replacement fuel in LPG engines. When appropriately controlled, hydrogen enrichment can deliver meaningful efficiency gains and emission reductions, supporting its role as a practical pathway toward lower-carbon power generation in fossil-fuel-dependent energy systems.

4. CONCLUSION

This study demonstrates that hydrogen enrichment is an effective and practical strategy to improve the performance and environmental profile of small-scale LPG-fueled power generation without major engine modifications. Using a combined experimental–numerical approach on a single-cylinder LPG engine–generator operating at 3000 rpm under steady-state loads, increasing hydrogen mass flow rate consistently enhanced combustion effectiveness, producing maximum gains of 12.2% in shaft power, 17.2% in torque, and 8.2% in brake mean effective pressure, while reducing specific fuel consumption by up to 13.1% and increasing thermal efficiency by up to 13.5% relative to LPG-only operation. Hydrogen addition also enabled leaner operation and reduced thermal stress indicators, with engine and lubricant temperatures decreasing by up to 12.2% and 8.3%, respectively, alongside measurable emission benefits, including maximum reductions of 8.2% in CO and 9.4% in HC. Collectively, these results confirm that hydrogen primarily functions as a combustion enhancer by accelerating flame propagation and promoting more complete oxidation, supporting LPG–hydrogen dual-fuel operation as a viable transitional pathway toward lower-carbon distributed power generation.

Daftar pustaka

Adeboye, B. S., Ogunlade, C. A., ADEDUNTAN, A. S., & Oyewo, A. T. (2025). Comparative Analysis of Engine Efficiency and Emission Using Premium Motor Spirit (PMS) and Liquefied Petroleum Gas (LPG) in Spark Ignition Engines. Uniosun Journal of Engineering and Environmental Sciences, 7(1). https://doi.org/10.36108/ujees/5202.70.0160

Aghahasani, M., Gharehghani, A., Andwari, A. M., Mikulski, M., Pesyridis, A., Megaritis, T., & Könnö, J. (2022). Numerical Study on Hydrogen–Gasoline

Dual-Fuel Spark Ignition Engine. Processes, 10(11), 2249. https://doi.org/10.3390/pr10112249

Al-Amoodi, T., Khalafalla, M., & Ahmed, S. F. (2024). LPG-Diesel Dual Fuel Emission Characteristics: A Review. Journal of Student Research, 13(1). https://doi.org/10.47611/jsr.v13i1.2368

Asiñero, D. M. M., Magomnang, A.-A. S. M., & Pabilona, L. L. (2023). Performance of Various Fuels: Gasoline, Liquefied Petroleum Gas and Biogas From Agricultural Biomass Waste in a Two-Stroke Internal Combustion Engine. MJST, 21(1). https://doi.org/10.61310/mndjstiect.0969.23

Baumgardner, M. E., Graves, A., Hilt, K., Larson, L. E., & Nordell, C. (2025). Increasing Efficiency and Reducing Emissions in a Small Displacement Gasoline Engine With Hydrogen-Enriched Natural Gas. 1(3). https://doi.org/10.1115/1.4067362

Beccari, S., & Pipitone, E. (2021). Detailed Combustion Analysis of a Supercharged Double-Fueled Spark Ignition Engine. Sae International Journal of Engines, 15(4), 499–513. https://doi.org/10.4271/03-15-04-0026

Beccari, S., Pipitone, E., & Caltabellotta, S. (2023). Analysis of the Combustion Process in a Hydrogen-Fueled CFR Engine. Energies, 16(5), 2351. https://doi.org/10.3390/en16052351

Bello, M. O., & Solarin, S. A. (2021). Searching for Sustainable Electricity Generation: The Possibility of Substituting Coal and Natural Gas With Clean Energy. Energy & Environment, 33(1), 64–84. https://doi.org/10.1177/0958305x20985253

Berni, F., Mortellaro, F., Pessina, V., Paltrinieri, S., Pulvirenti, F., Rossi, V., Borghi, M., & Fontanesi, S. (2022). Modeling of Gaseous Emissions and Soot in 3d-CFD in-Cylinder Simulations of Spark-Ignition Engines: A Methodology to Correlate Numerical Results and Experimental Data. International Journal of Engine Research, 24(5), 2149–2174. https://doi.org/10.1177/14680874221112564

Bhan, S. (2025). Optimization of SI Engine Responses Fueled With Hydrogen-enriched G30 Fuel: Experimental and Statistical Approach. Environmental Progress & Sustainable Energy. https://doi.org/10.1002/ep.70257

Bhowmik, S., Paul, A., & Panua, R. (2021). Effect of Pilot Fuel Injection Timing on the Performance, Combustion, and Exhaust Emissions of biodiesel–ethanol–diethyl Ether Blend Fueled CRDI Engine Under Hydrogen Dual Fuel

Strategies. Environmental Progress & Sustainable Energy, 41(4). https://doi.org/10.1002/ep.13784

Biondo, O., Fromentin, C., Silva, T., Guerra, V., Rooij, G. J. v., & Bogaerts, A. (2022). Insights Into the Limitations to Vibrational Excitation of CO 2: Validation of a Kinetic Model With Pulsed Glow Discharge Experiments. Plasma Sources Science and Technology, 31(7), 074003. https://doi.org/10.1088/1361-6595/ac8019

Birhanu, B. (2022). Enhancement and Analytical Assessment of Single Cylinder Spark Ignition Engine Operated on Liquefied Petroleum Gas (LPG). Journal of Electronics Computer Networking and Applied Mathematics, 21, 29–43. https://doi.org/10.55529/jecnam.21.29.43

Cai, K., Liu, Y., Chen, Q., Qi, Y., Li, L., & Wang, Z. (2023). Combustion Behaviors and Unregular Emission Characteristics in an Ammonia–Diesel Engine. Energies, 16(19), 7004. https://doi.org/10.3390/en16197004

Cernat, A., Pană, C., Negurescu, N., Nutu, C., Fuiorescu, D., & Lăzăroiu, G. (2023). Aspects of an Experimental Study of Hydrogen Use at Automotive Diesel Engine. Heliyon, 9(3), e13889. https://doi.org/10.1016/j.heliyon.2023.e13889

Chen, Q., Zheng, Z., & Zhu, Z. (2023). Effects of Syngas Addition on Combustion Characteristics of Gasoline Surrogate Fuel. Acs Omega, 8(4), 3929–3944. https://doi.org/10.1021/acsomega.2c06515

Cheng, Q., Ahmad, Z., Kaario, O., Vuorinen, V., & Larmi, M. (2022). Effect of Hydrogen Enhancement on Natural Flame Luminosity of Tri-Fuel Combustion in an Optical Engine. Energies, 15(23), 9080. https://doi.org/10.3390/en15239080

Deng, X., Tang, F., Zhu, H., Wan, G. C., Lei, J., & Jia, D. (2025). Numerical Simulation Study on the Influence of Spark Plug Position on Combustion Performance of a Cycloidal Rotary Engine. Journal of Energy Resources Technology Part a Sustainable and Renewable Energy, 2(1). https://doi.org/10.1115/1.4070073

Devarajan, Y., Nagappan, B., Choubey, G., Vellaiyan, S., & Mehar, K. (2021). Renewable Pathway and Twin Fueling Approach on Ignition Analysis of a Dual-Fuelled Compression Ignition Engine. Energy & Fuels, 35(12), 9930–9936. https://doi.org/10.1021/acs.energyfuels.0c04237

Frasci, E., Sementa, P., Arsie, I., Jannelli, E., & Vaglieco, B. M. (2023). Experimental and Numerical Investigation of the Impact of the Pure Hydrogen Fueling on

Fuel Consumption and NOx Emissions in a Small DI SI Engine. International Journal of Engine Research, 24(8), 3574–3587. https://doi.org/10.1177/14680874231162141

Georgescu, R., Pană, C., Negurescu, N., Cernat, A., Nuţu, C., & Sandu, C. (2023). Theoretical and Experimental Research on the Use of Hydrogen in the Automotive Spark Ignition Engine. Iop Conference Series Materials Science and Engineering, 1290(1), 012010. https://doi.org/10.1088/1757-899x/1290/1/012010

Georgescu, R., Pană, C., Negurescu, N., Cernat, A., Nuţu, C., & Sandu, C. (2024). The Influence of Hydrogen Addition on a SI Engine—Theoretical and Experimental Investigations. Sustainability, 16(16), 6873. https://doi.org/10.3390/su16166873

Giacomazzi, E., Troiani, G., Nardo, A. D., Calchetti, G., Cecere, D., Messina, G., & Carpenella, S. (2023). Hydrogen Combustion: Features and Barriers to Its Exploitation in the Energy Transition. Energies, 16(20), 7174. https://doi.org/10.3390/en16207174

Gianetti, G. G., Lucchini, T., D'Errico, G., Onorati, A., & Soltic, P. (2023). Development and Validation of a CFD Combustion Model for Natural Gas Engines Operating With Different Piston Bowls. Energies, 16(2), 971. https://doi.org/10.3390/en16020971

Guleria, G., Pintor, D. L., Dec, J. E., & Assanis, D. (2021). A Comparative Study of Gasoline Skeletal Mechanisms Under Partial Fuel Stratification Conditions Using Large Eddy Simulations. International Journal of Engine Research, 23(10), 1658–1677. https://doi.org/10.1177/14680874211031370

Guo, H., Torelli, R., Szybist, J. P., & Som, S. (2021). CFD Modeling of Pre-Spark Heat Release in a Boosted Direct-Injection Spark-Ignition Engine. International Journal of Engine Research, 24(1), 3–15. https://doi.org/10.1177/14680874211044110

Guo, M., Chen, B., & Hamm, N. (2023). Analysis of the Spatiotemporal Heterogeneity of Drivers on Province-Level Synergy of Air Pollution Control and Carbon Mitigation in China. Isprs Annals of the Photogrammetry Remote Sensing and Spatial Information Sciences, X-1/W1-2023, 509–516. https://doi.org/10.5194/isprs-annals-x-1-w1-2023-509-2023

Hadjkacem, S., Jemni, M. A., Driss, Z., & Abid, M. S. (2023). Biomimetic Swirl Device and Hydrogen Enrichment Effects on LPG Fueled Engine. International

Journal of Engine Research, 25(4), 803–813. https://doi.org/10.1177/14680874231209399

Halewadimath, S. S., Banapurmath, N. R., Yaliwal, V. S., Gaitonde, V. N., Khan, T. M. Y., Vadlamudi, C., Krishnappa, S., & Sajjan, A. M. (2023). Experimental Investigations on Dual-Fuel Engine Fueled With Tertiary Renewable Fuel Combinations of Biodiesel and Producer—Hydrogen Gas Using Response Surface Methodology. Sustainability, 15(5), 4483. https://doi.org/10.3390/su15054483

Haque, M. A., Hasan, M. K., & Mahamud, R. (2025). A High-Order Compact Finite Difference Scheme for Flamelet-Based Scalar Transport in Non-Premixed Laminar Flames. Physics of Fluids, 37(8). https://doi.org/10.1063/5.0283534

Hoecke, L. V., Boeye, D., González-Quiroga, A., Patience, G. S., & Perreault, P. (2022). Experimental Methods in Chemical Engineering: Computational Fluid Dynamics/Finite Volume Method—CFD/FVM. The Canadian Journal of Chemical Engineering, 101(2), 545–561. https://doi.org/10.1002/cjce.24571

Impact of Fuel Injection Pressure on GDI Engine Performance: A Numerical Study With Pre-Combustion Chamber. (2024). International Journal of Advanced Technology and Engineering Exploration, 11(119). https://doi.org/10.19101/ijatee.2023.10102577

Jeong, S.-J. (2024). CFD Simulation of Pre-Chamber Spark-Ignition Engines—A Perspective Review. Energies, 17(18), 4696. https://doi.org/10.3390/en17184696

Kalvakala, K. C., Singh, H., Pal, P., González, J. P., Kolodziej, C. P., & Aggarwal, S. K. (2024). Computational Study on the Impact of Gasoline-Ethanol Blending on Autoignition and Soot/No x Emissions Under Low-Load Gasoline Compression Ignition Conditions. International Journal of Engine Research, 26(3), 370–385. https://doi.org/10.1177/14680874241286268

Khandal, S. V., Khan, T. M. Y., Kamangar, S., Baig, M. A. A., & J, S. A. N. (2021). Effects of Hydrogen Flow Rate, Injection Pressure and EGR on Performance of Common Rail Direct Injection (CRDi) Engine in Dual Fuel Mode. Frontiers in Engineering and Built Environment, 1(1), 81–96. https://doi.org/10.1108/febe-02-2021-0007

Khudhur, F. A. (2025). Comparative Emissions of Syngas, Biogas, and LPG in Spark-Ignition Engines for Sustainable Power Generation. Engineering Technology

& Applied Science Research, 15(6), 28635–28639. https://doi.org/10.48084/etasr.13864

Kiwan, B., Kalib, N. S., & Muchtar, A. (2022). Decomposition and Decoupling Analyses of CO2 Emissions and Economic Growth: A Comparative Study Between Malaysia and Vietnam. Iop Conference Series Materials Science and Engineering, 1257(1), 012021. https://doi.org/10.1088/1757-899x/1257/1/012021

Krishnan, R. A., Panda, K., & Ramesh, A. (2024). Investigations on the Effects of Injection Parameters and EGR in a Glow Plug Assisted Methanol Fueled Hot Surface Ignition (HSI) Engine. International Journal of Engine Research, 25(9), 1641–1658. https://doi.org/10.1177/14680874241241564

Kumar, S., Srinivas, V. G., Murthy, K., & Sudheer, M. S. (2021). Simulation and Experimental Validation of Combustion Characteristics of Dual Fuel LPG-Diesel Engine. International Journal of Heat and Technology, 39(6), 1937–1944. https://doi.org/10.18280/ijht.390631

Laget, O., Rouleau, L., Cordier, M., Duffour, F., Maio, G., Giuffrida, V., Kumar, R., & Nowak, L. (2023). A Comprehensive Study for the Identification of the Requirements for an Optimal H2 Combustion Engine. International Journal of Engine Research, 24(10), 4326–4342. https://doi.org/10.1177/14680874231167618

Lanotte, A., Bellis, V. D., & Malfi, E. (2021). Potential of Hydrogen Addition to Natural Gas or Ammonia as a Solution Towards Low- Or Zero-Carbon Fuel for the Supply of a Small Turbocharged SI Engine. E3s Web of Conferences, 312, 07022. https://doi.org/10.1051/e3sconf/202131207022

Leonardo, A., & Semin, S. (2022). Effect of CNG Engine Conversion on Performance Characteristic: A Review. Iop Conference Series Earth and Environmental Science, 972(1), 012028. https://doi.org/10.1088/1755-1315/972/1/012028

Ling, Y., Xia, S., Cao, M., He, K., Lim, M. K., Sukumar, A., Yi, H., & Qian, X.-D. (2021). Carbon Emissions in China’s Thermal Electricity and Heating Industry: An Input-Output Structural Decomposition Analysis. Journal of Cleaner Production, 329, 129608. https://doi.org/10.1016/j.jclepro.2021.129608

Madia, M., Cicalese, G., & Dalseno, L. (2023). Hydrogen, Methane and One of Their Fuel Blends Combustion: CFD Analysis and Numerical-Experimental Comparisons of Fixed and Mobile Applications. Journal of Physics Conference Series, 2648(1), 012080. https://doi.org/10.1088/1742-6596/2648/1/012080

Mahmood, A. S., Allawi, M. K., & Imran, M. S. (2025). Numerical and Experimental Study of the Spark Ignition Engine Performance Using Different Types of Liquid and Gaseous Fuels. Heat Transfer, 54(6), 4036–4048. https://doi.org/10.1002/htj.23398

Maio, G., Boberic, A., Giarracca, L., Aubagnac-Karkar, D., Colin, O., Duffour, F., Deppenkemper, K., Virnich, L., & Pischinger, S. (2022). Experimental and Numerical Investigation of a Direct Injection Spark Ignition Hydrogen Engine for Heavy-Duty Applications. International Journal of Hydrogen Energy, 47(67), 29069–29084. https://doi.org/10.1016/j.ijhydene.2022.06.184

Manni, U. H. & Datuk. Dr. Kasim Hj. Md. Mansur. (2023). Identifying the Drivers Responsible for Energy Security in Selected ASEAN Countries by Using Panel Data Analysis. International Journal of Energy Sector Management, 18(3), 658–682. https://doi.org/10.1108/ijesm-02-2023-0004

Mohamed, M., Biswal, A., Wang, X., Zhao, H., Harrington, A., & Hall, J. (2024). Unveiling the Potential of Hydrogen in a Downsized Gasoline Direct Injection Engine Performance and Emissions Experimental Study. Sae International Journal of Fuels and Lubricants, 17(3). https://doi.org/10.4271/04-17-03-0015

Mohsen, M. J., & Al-Dawody, M. F. (2022). Effect of Using LPG of Diesel Engine: A Review. Periódico Tchê Química, 19(41), 48–62. https://doi.org/10.52571/ptq.v19.n41.2022.05_mohsen_pgs_48_62.pdf

Muhammad, S., Ali, U., Farid, M., & Mukhtar, T. (2021). Experimental Investigation of Performance and Emissions of Spark Ignition Engine Fueled With Blends of HHO Gas With Gasoline and CNG. International Journal of Sustainable Water and Environmental Systems, 18(1). https://doi.org/10.5383/ijtee.18.01.004

Muhssen, H. S., Zöldy, M., & Bereczky, Á. (2024). A Comprehensive Review on the Hydrogen–Natural Gas–Diesel Tri-Fuel Engine Exhaust Emissions. Energies, 17(15), 3862. https://doi.org/10.3390/en17153862

Nguyen, Q. T., & Le, M. D. (2022). Effects of Compression Ratios on Combustion and Emission Characteristics of SI Engine Fueled With Hydrogen-Enriched Biogas Mixture. Energies, 15(16), 5975. https://doi.org/10.3390/en15165975

Nguyen, T. H., Balasubramanian, D., Venugopal, I. P., Le, T. T., Le, H. C., Truong, T. H., & Cao, D. N. (2025). A Comprehensive Review of Compressed Natural Gas (CNG)-fueled Engines Under Different Operating Conditions and Combustion Strategies on Performance and Combustion Characteristics.

Energy & Environment, 36(3), 1536–1576. https://doi.org/10.1177/0958305x251315402

Ortiz-Imedio, R., Ortiz, A., & Ortíz, I. (2022). Comprehensive Analysis of the Combustion of Low Carbon Fuels (Hydrogen, Methane and Coke Oven Gas) in a Spark Ignition Engine Through CFD Modeling. Energy Conversion and Management, 251, 114918. https://doi.org/10.1016/j.enconman.2021.114918

Ozkara, M., & Gül, M. Z. (2025). Optimization of a Heavy-Duty Hydrogen-Fueled Internal Combustion Engine Injector for Optimum Performance and Emission Level. Applied Sciences, 15(15), 8131. https://doi.org/10.3390/app15158131

Pal, P., Kumar, G., Drennan, S. A., Rankin, B. A., & Som, S. (2021). Multidimensional Numerical Modeling of Combustion Dynamics in a Non-Premixed Rotating Detonation Engine With Adaptive Mesh Refinement. Journal of Energy Resources Technology, 143(11). https://doi.org/10.1115/1.4050590

Pandey, V., Shahapurkar, K., Guluwadi, S., Mengesha, G. A., Gadissa, B., Banapurmath, N. R., Vadlamudi, C., Krishnappa, S., & Khan, T. M. Y. (2023). Studies on the Performance of Engines Powered With Hydrogen-Enriched Biogas. Energies, 16(11), 4349. https://doi.org/10.3390/en16114349

Paykani, A. (2021). Comparative Study on Chemical Kinetics Mechanisms for Methane-Based Fuel Mixtures Under Engine-Relevant Conditions. Energies, 14(10), 2834. https://doi.org/10.3390/en14102834

Piano, A., Rolando, L., Roggio, S., Millo, F., Tonelli, R., Gullino, F., & Mortellaro, F. S. (2024). Experimental and Numerical Investigation of Abnormal Combustion Phenomena in High-Performance Hydrogen Direct-Injection Engine Operated in Stochiometric Conditions. International Journal of Engine Research, 26(7), 1017–1028. https://doi.org/10.1177/14680874241302562

Pukalskas, S., Kriaučiūnas, D., Rimkus, A., Przybyła, G., Dróździel, P., & Barta, D. (2021). Effect of Hydrogen Addition on the Energetic and Ecologic Parameters of an SI Engine Fueled by Biogas. Applied Sciences, 11(2), 742. https://doi.org/10.3390/app11020742

Pukalskas, S., Rimkus, A., Vipartas, T., Stravinskas, S., Kriaučiūnas, D., Mejeras, G., & Ušinskas, A. (2025). Hydrogen Supplementation in SI Engines: Enhancing Efficiency and Reducing Emissions With a Focus on Knock Phenomena. Machines, 13(7), 571. https://doi.org/10.3390/machines13070571

Rajak, U., Nashine, P., Chaurasiya, P. K., & Verma, T. N. (2021). A Numerical Investigation of the Species Transport Approach for Modeling of Gaseous Combustion. Journal of Thermal Engineering, 7(Supp 14), 2054–2067. https://doi.org/10.18186/thermal.1051312

Şimşek, S., & Uslu, S. (2024). Evaluation of the Possible Effects of Varying the Volumetric Ratio of LPG on the Spark Ignition Engine's Performance, Emissions, and Combustion. International Journal of Automotive Science and Technology, 8(3), 273–278. https://doi.org/10.30939/ijastech..1491371

Şimşek, S., Uslu, S., & Şimsek, H. (2021). Experimental Study on the Ability of Different Biogas Level Dual Fuel Spark Ignition Engine: Emission Mitigation, Performance, and Combustion Analysis. Oil & Gas Science and Technology – Revue D'ifp Energies Nouvelles, 76, 74. https://doi.org/10.2516/ogst/2021060

Stipić, M., Basara, B., Schmidt, S. J., & Adams, N. A. (2023). Tabulated Chemistry Combustion Model for Cost-Effective Numerical Simulation of Dual-Fuel Combustion Process. Energies, 16(24), 8040. https://doi.org/10.3390/en16248040

Tamang, S., & Park, H. (2025). Numerical Investigation on the Dry Low NOx of Hydrogen Combustion. Journal of Physics Conference Series, 2968(1), 012009. https://doi.org/10.1088/1742-6596/2968/1/012009

Teodosio, L., Berni, F., Lanotte, A., & Malfi, E. (2022). 1d/3d Simulation Procedure to Investigate the Potential of a Lean Burn Hydrogen Fuelled Engine. Journal of Physics Conference Series, 2385(1), 012085. https://doi.org/10.1088/1742-6596/2385/1/012085

Tuấn, N. T., & Tho, D. P. (2023). Hc Emission Stable and Power Optimation of the Motorcycle LPG Engine by Heat Transfer to the Injector. Asean Engineering Journal, 13(2), 47–52. https://doi.org/10.11113/aej.v13.18596

Ugliano, E., Bozza, F., & Teodosio, L. (2024). Virtual Development of a Multi-Cylinder Hydrogen Spark Ignition Engine Operating at Lean Burn Conditions. Journal of Physics Conference Series, 2893(1), 012100. https://doi.org/10.1088/1742-6596/2893/1/012100

Wang, F., Harindintwali, J. D., Yuan, Z., Wang, M., Wang, F., Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., Chang, S. X., Zhang, L., Rinklebe, J., Yuan, Z., Zhu, Q., Xiang, L., Tsang, D. C., Xu, L., Jiang, X., … Chen, J. M. (2021). Technologies and Perspectives for Achieving Carbon Neutrality. The Innovation, 2(4), 100180. https://doi.org/10.1016/j.xinn.2021.100180

Wu, C., Sun, S., Cui, Y., & Xing, S. (2024). Driving Factors Analysis and Scenario Prediction of CO2 Emissions in Power Industries of Key Provinces Along the Yellow River Based on LMDI and BP Neural Network. Frontiers in Ecology and Evolution, 12. https://doi.org/10.3389/fevo.2024.1362541

Yaliwal, V. S., & Banapurmath, N. R. (2021). Combustion and Emission Characteristics of a Compression Ignition Engine Operated on Dual Fuel Mode Using Renewable and Sustainable Fuel Combinations. Sn Applied Sciences, 3(1). https://doi.org/10.1007/s42452-020-03987-2

Yotchou, G. V. T., Banta, N. J. I., Karanja, S. K., & Abbe, C. V. N. (2023). Experimental Study on the Effect of Load and Air+gas/Fuel Ratio on the Performances, Emissions and Combustion Characteristics of Diesel–LPG Fuelled Single Stationary Ci Engine. Engineering Reports, 5(9). https://doi.org/10.1002/eng2.12654

Yu, C., & Valera-Medina, A. (2024). A Comprehensive Numerical Study on the Inhibition Effect of Ammonia on Various (Un)strained Premixed Stoichiometric Hydrogen/Air Flame Systems. Energy & Fuels, 39(1), 981–991. https://doi.org/10.1021/acs.energyfuels.4c04052

Zheng, J., Zhang, C., Cai, P., Li, Y., & Wang, J. (2021). Construction of a Reduced Diesel/Polyoxymethylene Dimethyl Ether 3 (PODE3) Reaction Mechanism for Combustion and Emission Analysis. Energy & Fuels, 35(5), 4437–4446. https://doi.org/10.1021/acs.energyfuels.0c02935

Zhou, W., Zhou, S., Xi, H., Shreka, M., & Zhang, Z. (2021). Development of a Reduced Methane–Hydrogen–Polyoxymethylene Dimethyl Ether Mechanism Under Engine-Relevant Conditions. Acs Omega, 6(47), 31499–31512. https://doi.org/10.1021/acsomega.1c03763.