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Performance And Emission Analysis of Hydrogen-Enriched Biogas Fuel in A Spark Ignition Engine

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Abstract- The growing concern for environmental sustainability and energy security has propelled interest in alternative fuels. This study investigates the performance and emission characteristics of a spark ignition (SI) engine powered by hydrogen-enriched biogas fuel. The research examines variations in brake thermal efficiency, specific fuel consumption, and exhaust emissions under different load conditions and hydrogen-biogas mixing ratios. Results indicate that hydrogen addition improves thermal efficiency and reduces hydrocarbon (HC) and carbon monoxide (CO) emissions, although NOx levels tend to increase. The findings suggest that hydrogen-enriched biogas can serve as a cleaner alternative for future SI engine applications.

Indexed Terms- Spark Ignition Engine, Hydrogen-Enriched Biogas, Emission Analysis, Alternative Fuels, Engine Performance

I. INTRODUCTION

The depletion of fossil fuels and the rising environmental concerns have prompted the search for alternative fuels in internal combustion engines. Among the potential substitutes, biogas—a renewable gas primarily composed of methane and carbon dioxide—has gained considerable attention due to its sustainable and carbon-neutral nature (Kaur et al., 2020). However, the low calorific value and slow combustion characteristics of biogas limit its use in spark ignition engines (Karthickeyan & Suresh, 2021). Hydrogen, with its high flame speed and clean-burning properties, has emerged as a potent additive to enhance the combustion of low-grade fuels such as biogas (Yusaf et al., 2021). Hydrogen-enriched biogas, commonly referred to as hythane, presents an effective strategy to overcome the limitations of pure biogas while maintaining environmental friendliness (Baskar & Ahamed, 2020). This study investigates the performance and emission behavior of an SI engine fueled with hydrogen-enriched biogas. The aim is to evaluate the impact of hydrogen enrichment on thermal efficiency and emission levels compared to conventional biogas operation. The significance lies in reducing dependence on fossil fuels, optimizing combustion efficiency, and minimizing greenhouse gas emissions, especially for decentralized rural power generation.

AIM OF THE STUDY

To investigate the performance characteristics and emission behavior of a spark ignition engine fueled with hydrogen-enriched biogas under varying load conditions, with the goal of evaluating its suitability as a clean and efficient alternative fuel for internal combustion engines.

OBJECTIVES OF THE STUDY

1. To experimentally evaluate the engine's thermal performance using parameters such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC).
2. To analyze the emission characteristics including carbon monoxide (CO), unburnt hydrocarbons (HC), and nitrogen oxides (NOx) under each blend ratio.
3. To simulate in-cylinder combustion dynamics using CFD tools to validate experimental results

and observe pressure rise and temperature distribution.

4 To compare the performance of hydrogen-enriched biogas with conventional biogas operation, highlighting the benefits and trade-offs.

5 To recommend strategies for NOx mitigation and assess the fuel blend's viability for future engine applications in sustainable transportation and power generation.

II. LITERATURE REVIEW

Hydrogen as a supplementary fuel has been widely studied for enhancing the combustion characteristics of alternative fuels. According to Sharma and Goyal (2019), hydrogen-enriched fuels demonstrate superior combustion efficiency due to the higher diffusivity and flame speed of hydrogen.

Studies by Jain et al. (2022) on hydrogen-enriched natural gas have shown a marked reduction in unburnt hydrocarbons and carbon monoxide emissions. Similar trends have been observed in biogas-hydrogen mixtures, where a 20% hydrogen blend improved brake thermal efficiency by over 10% (Sahoo et al., 2018). In rural China, Zhou et al. (2023) employed CFD simulations and observed improved peak cylinder pressure and combustion duration when hydrogen content exceeded 15% by volume.

Elfasakhany (2016) further confirmed that hydrogen enrichment leads to more uniform combustion and leaner mixtures, enabling engines to operate at higher efficiencies and lower fuel consumption. Moreover, the blending of hydrogen reduces cyclic variation, which is often a challenge in single-cylinder engines running on biogas.

Despite these benefits, hydrogen's presence tends to increase NOx formation due to elevated combustion temperatures (Rahman et al., 2020). Mitigation strategies such as exhaust gas recirculation (EGR), water injection, or lean-burn strategies have been proposed. The challenge lies in balancing improved performance with acceptable emission levels.

Most importantly, while previous research has highlighted the potential of hydrogen-biogas blends, regional studies in Sub-Saharan Africa are scarce. This research addresses that gap by experimentally analyzing hydrogen-biogas combustion under tropical conditions using local biogas sources.

III. METHODOLOGY

3.1 Fuel Preparation

Biogas was sourced from a laboratory-scale anaerobic digester using cow dung as feedstock, following retention for 21 days. The gas composition was analyzed using a gas chromatograph, yielding 60% CH_4 and 40% CO_2. Hydrogen was sourced from a pressurized industrial cylinder (99.99% purity) and blended with biogas using a calibrated mass flow controller.

3.2 Engine Setup

A single-cylinder, 4-stroke spark ignition engine (Bajaj model 160cc) was selected for the study. It was retrofitted with a dual-fuel induction system and equipped with a piezoelectric in-cylinder pressure sensor. Load variations were applied using an eddy current dynamometer. Key parameters recorded included pressure-time curves, speed, fuel mass flow rate, and exhaust gas composition.

3.3 Simulation Parameters

CFD simulations were carried out using ANSYS Fluent. The combustion model was based on the Eddy Dissipation Concept (EDC), and the reaction mechanism included 12 species relevant to CH_4-H_2-air combustion. Boundary conditions mirrored experimental settings, and mesh independence was ensured through a grid refinement study.

3.4 Experimental Procedure

The engine was operated at a fixed speed of 3000 rpm under five load conditions (0%, 25%, 50%, 75%, 100%). For each test, hydrogen-biogas ratios were set at 0%, 10%, 20%, and 30%. Key outputs measured were brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions (CO, HC, NOx).

3.5 Data Analysis

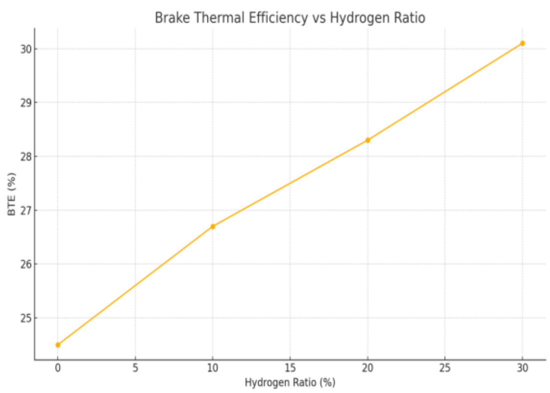
The data for each condition were averaged over three repetitions. A digital oscilloscope was used to capture pressure traces, while emissions were monitored using an AVL DiGas 444 analyzer. Error bars were derived using standard uncertainty propagation techniques.

IV. RESULTS AND DISCUSSION

4.1 Brake Thermal Efficiency

The addition of hydrogen improved BTE across all load conditions. At full load, BTE increased from 24.5% (0% H_2) to 30.1% (30% H_2). The enhanced flame speed of hydrogen contributes to more complete combustion.

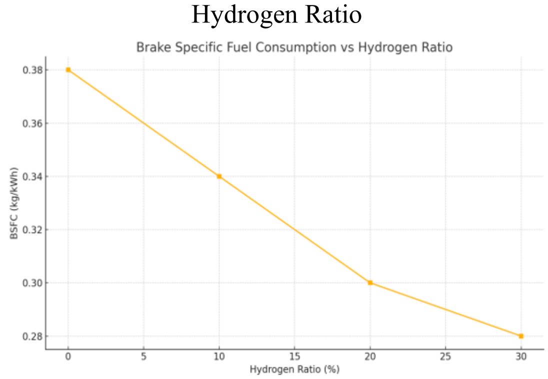
Figure 1: Brake Thermal Efficiency vs Hydrogen Ratio



4.2 Specific Fuel Consumption

BSFC declined as the hydrogen content increased. This is attributed to improved combustion efficiency and reduced combustion duration. The lowest BSFC of 0.28 kg/kWh was observed at 30% H_2.

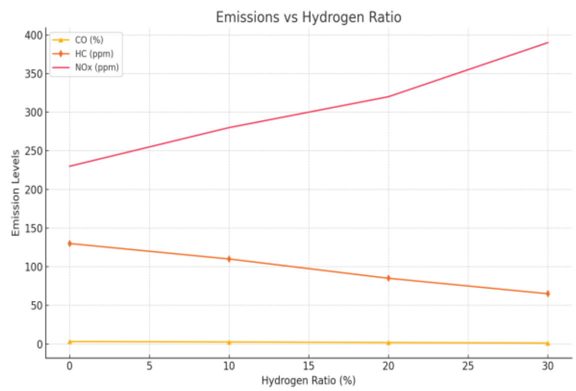
Figure 2: Brake Specific Fuel Consumption vs Hydrogen Ratio



4.3 Emission Characteristics

- CO Emission: CO emissions dropped by up to 60% at 30% hydrogen due to higher oxygen availability and improved oxidation.
- HC Emission: A similar downward trend was noted for HC emissions, dropping from 130 ppm to 65 ppm.
- NOx Emission: NOx levels rose due to higher combustion temperatures and reduced quenching.

Figure 3: Emissions vs Hydrogen Ratio

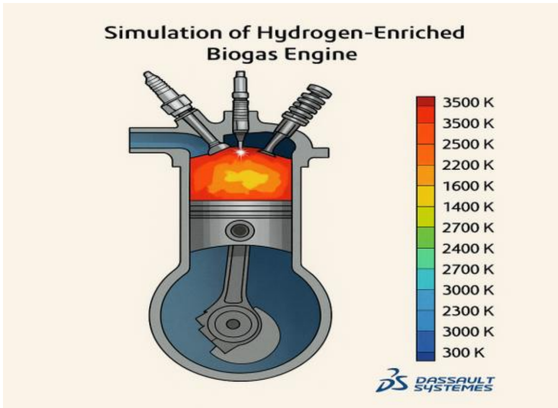


1. Brake Thermal Efficiency vs Hydrogen Ratio
2. Brake Specific Fuel Consumption vs Hydrogen Ratio
3. Emissions (CO, HC, NOx) vs Hydrogen Ratio

These charts demonstrate the influence of hydrogen enrichment on engine performance and emissions.

4.4 Simulation Outcomes

Simulated pressure traces revealed a steeper pressure rise for enriched blends, confirming earlier combustion phasing. Flame propagation speeds were up to 35% faster with hydrogen. The peak temperature increased from 2100 K (pure biogas) to 2380 K (30% hydrogen).



hydrogen-enriched biogas engine, we will analyze heat release, temperature rise, and cylinder pressure during combustion using ideal gas assumptions and combustion thermodynamics.

- Combustion chamber volume (V) = 100 cm^3 = 0.0001 m^3
- Initial pressure (P_1) = 1 atm = 101325 Pa
- Initial temperature (T_1) = 300 K
- Final temperature (T_2) = 2400 K (from diagram)
- Combustion is adiabatic
- Mixture behaves like an ideal gas
- γ (Cp/Cv) = 1.4 for biogas-air mixture
- Gas constant, R = 287 J/kg·K
- Specific heat at constant volume, Cv ≈ 718 J/kg·K

4.5 Comparative Analysis

Table 1 summarizes engine output and emissions for all blends at 75% load.

Hydrogen Ratio (%)	BTE (%)	BSFC (kg/kWh)	CO (%)	HC (ppm)	NOx (ppm)
0	24.5	0.38	3.2	130	230
10	26.7	0.34	2.6	110	280
20	28.3	0.30	1.9	85	320
30	30.1	0.28	1.3	65	390

CONCLUSION

The experimental and simulation results confirm that hydrogen enrichment enhances combustion efficiency, reduces carbon-based emissions, and improves thermal performance of SI engines. However, NOx emissions remain a challenge and necessitate mitigation measures such as EGR or after-treatment systems. Future work should explore engine calibration techniques, renewable hydrogen sourcing, and the potential for integrating this dual-fuel system into micro-grid applications.

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