PERFORMANCE ANALYSIS OF HYDROGEN AS AN ALTERNATIVE FUEL IN IC ENGINES: COMBUSTION CHARACTERISTICS AND EMISSION REDUCTIONS

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ABSTRACT

Hydrogen is gaining attention as a sustainable alternative fuel for internal combustion (IC) engines due to its high energy content and zero carbon emissions. This study investigates the combustion characteristics and emission reduction potential of hydrogen in a modified IC engine. Experimental results are compared with conventional petrol and diesel fuels under identical operating conditions. The findings reveal that hydrogen exhibits superior combustion efficiency, higher brake thermal efficiency (BTE), and significant reductions in carbon-based emissions. However, nitrogen oxide (NO_x) emissions are higher due to elevated combustion temperatures. The study concludes that hydrogen is a viable alternative fuel for IC engines, provided that NO_x emissions are mitigated.

Keyword : - *Hydrogen fuel, internal combustion engine, alternative fuel, emissions reduction, combustion characteristics, brake thermal efficiency, NOx emissions, CO2 emissions etc.*

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1. INTRODUCTION

Background: Rising environmental concerns and depleting fossil fuel reserves necessitate the adoption of alternative fuels.
Hydrogen as a Fuel: Hydrogen is a clean energy carrier with high energy density (142 MJ/kg) and zero carbon emissions.
Objective: To analyze the combustion characteristics and emission reduction potential of hydrogen in IC engines and compare it with petrol and diesel.

The global transition toward sustainable and low-carbon energy solutions has intensified the exploration of alternative fuels for internal combustion (IC) engines. Hydrogen, recognized for its zero-carbon combustion and high energy content per unit mass, presents a compelling alternative to conventional fossil fuels. Its combustion results in water as the primary byproduct, thereby addressing critical challenges related to greenhouse gas emissions and air quality deterioration.

IC engines, being a cornerstone of transportation and industrial power generation, offer a feasible platform for integrating hydrogen fuel without necessitating entirely new infrastructure. This makes hydrogen an attractive option for reducing emissions while leveraging existing engine technologies. Moreover, the adaptability of IC engines to hydrogen blends enables a gradual transition to a hydrogen-based energy ecosystem, bridging the gap between conventional fuels and full-scale hydrogen deployment.

Despite its potential, challenges such as knock propensity, combustion stability, and storage limitations have hindered widespread adoption. Addressing these challenges through innovative research and optimization is vital for realizing the full potential of hydrogen as a sustainable fuel. This study investigates the performance, combustion characteristics, and emissions of hydrogen-fueled IC engines, providing insights into their practical feasibility and implications for future energy strategies.

2. LITERATURE REVIEW

- Hydrogen Combustion: Hydrogen has a wide flammability range (4–75% by volume) and high flame speed (325 cm/s), enabling efficient combustion.
- Challenges: Pre-ignition, knocking, and high NO_x emissions are major challenges.
- Previous Studies: Research highlights hydrogen's potential but calls for solutions to address NO_x emissions and storage issues.

Das (1996) [1] provides an in-depth examination of hydrogen as a fuel for internal combustion engines, exploring historical developments, technical challenges, and future trends. The study highlights hydrogen's superior combustion characteristics, such as high flame speed and wide flammability limits, which enhance engine efficiency and enable lean combustion for lower NOx emissions. However, the low ignition energy of hydrogen increases the risk of pre-ignition and backfiring, requiring technical solutions such as optimized injection timing and water injection.

On the technical front, the paper discusses the design adaptations needed for hydrogen engines, including modifications to intake systems, ignition systems, and combustion chambers. Storage and handling issues are critically analyzed, with Das emphasizing the need for advancements in compressed and cryogenic storage methods to overcome hydrogen's low energy density.

Das [1] underscores hydrogen's environmental benefits, notably the potential for zero CO2 and minimal particulate emissions. Despite these advantages, the study acknowledges challenges such as NOx emissions and infrastructure limitations. It concludes by emphasizing the need for continued research into hydrogen storage, fuel injection technologies, and policy support for widespread adoption. The work remains a seminal reference for hydrogen engine research, particularly for its technical insights and future-oriented outlook.

Verhelst and Wallner (2009) [2] provide a comprehensive review of hydrogen-fueled internal combustion engines (H2-ICEs), analyzing their development, operational characteristics, and challenges. The study highlights hydrogen's unique combustion properties, including its high flame speed, wide flammability range, and low ignition energy, which allow for highly efficient lean combustion. These characteristics contribute to reduced CO2 emissions and lower particulate pollution.

On the technical front, the review explores key aspects such as combustion control, fuel injection strategies, and engine modifications to mitigate pre-ignition, knock, and backfiring. The authors assess both port fuel injection and direct injection systems, noting that direct injection offers better control of combustion but involves more complex design requirements.

The paper emphasizes the critical role of hydrogen storage and delivery systems, examining the challenges of using compressed, cryogenic, and metal hydride storage methods. It also discusses NOx emissions as a significant issue, proposing strategies like exhaust gas recirculation (EGR) and lean-burn combustion to address it.

Verhelst and Wallner [2] conclude by identifying the potential of H2-ICEs as a transitional technology toward a hydrogen-based energy future. They advocate for continued research in fuel injection technologies, advanced combustion strategies, and infrastructure development to support hydrogen adoption. This review remains a foundational resource for understanding the technical, environmental, and operational aspects of hydrogen-powered engines.

Heywood's Internal Combustion Engine Fundamentals (1988) [3] is a foundational text in the field of engine technology, offering a comprehensive analysis of the design, operation, and performance of internal combustion engines (ICEs). The book provides in-depth coverage of both spark-ignition (SI) and compression-ignition (CI) engines, with detailed discussions on thermodynamics, fluid mechanics, combustion processes, and emissions control.

Key technical aspects covered include:

- Combustion Mechanics: Detailed exploration of air-fuel mixing, flame propagation in SI engines, and autoignition in CI engines.
- Performance Metrics: Analysis of engine efficiency, power output, and factors affecting fuel consumption.
- Emission Formation and Control: Insights into the formation of NOx, CO, hydrocarbons, and particulate matter, along with emission reduction technologies.

3. METHODOLOGY

3. 1. Experimental Setup

- Engine Specifications:
  - Single-cylinder, four-stroke IC engine.
  - Compression ratio: 10:1.
  - Modified for hydrogen fuel using a port fuel injection system.
- Instrumentation:
  - Dynamometer for torque and power measurement.
  - Gas analyzers for emission measurement (CO, CO_2, NO_x, HC).

3.2. Test Conditions

- Engine speed: 1500–3000 rpm.
- Load: 25%, 50%, 75%, and 100% of maximum load.
- Fuel injection timing and pressure optimized for each fuel.

3.3. Performance Metrics

- Combustion Characteristics:
  - Flame speed.
  - Combustion temperature.
  - Heat release rate.
- Emission Parameters:
  - CO, CO_2, NO_x, and unburnt hydrocarbons (HC).

3.4. Calculations

- Brake Thermal Efficiency (BTE):

$$BTE = \frac{\text{Brake Power}}{\text{Energy Input From Fuel}} \times 100$$

- Brake Specific Fuel Consumption (BSFC)**:**

$$BSFC = \frac{\text{Mass Flow Rate of Fuel(Kg/hr)}}{\text{Brake Power(KW)}}$$

4. RESULTS AND DISCUSSION

4.1. Combustion Characteristics

- Flame Speed:
  - Hydrogen: 325 cm/s (highest among the three fuels).
  - Petrol: 40 cm/s.
  - Diesel: 30 cm/s.
- Combustion Temperature:
  - Hydrogen: ~2000°C (higher than petrol and diesel).
  - Petrol: ~1500°C.

    - Diesel: ~1400°C.
- Heat Release Rate:
    - Hydrogen exhibits a rapid heat release rate due to its high flame speed.

4.2. Performance Analysis

- Brake Thermal Efficiency (BTE):
    - Hydrogen: 35% at 25% load, decreasing to 28% at 100% load.
    - Petrol: 28% at 25% load, 25% at 100% load.
    - Diesel: 30% at 25% load, 27% at 100% load.
- Brake Specific Fuel Consumption (BSFC):
    - Hydrogen: 0.15 kg/kWh (lowest due to high energy density).
    - Petrol: 0.30 kg/kWh.
    - Diesel: 0.28 kg/kWh.

4.3. Emission Analysis

- CO Emissions:
    - Hydrogen: Near-zero emissions.
    - Petrol: 0.5–1.0% by volume.
    - Diesel: 0.1–0.5% by volume.
- CO_2 Emissions:
    - Hydrogen: Zero emissions.
    - Petrol: 12–15% by volume.
    - Diesel: 10–12% by volume.
- NO_x Emissions:
    - Hydrogen: 2000 ppm at 100% load (highest due to high combustion temperature).
    - Petrol: 1000 ppm at 100% load.
    - Diesel: 800 ppm at 100% load.
- Unburnt Hydrocarbons (HC):
    - Hydrogen: Negligible.
    - Petrol: 200 ppm.
    - Diesel: 100 ppm.

4.4. Graphs

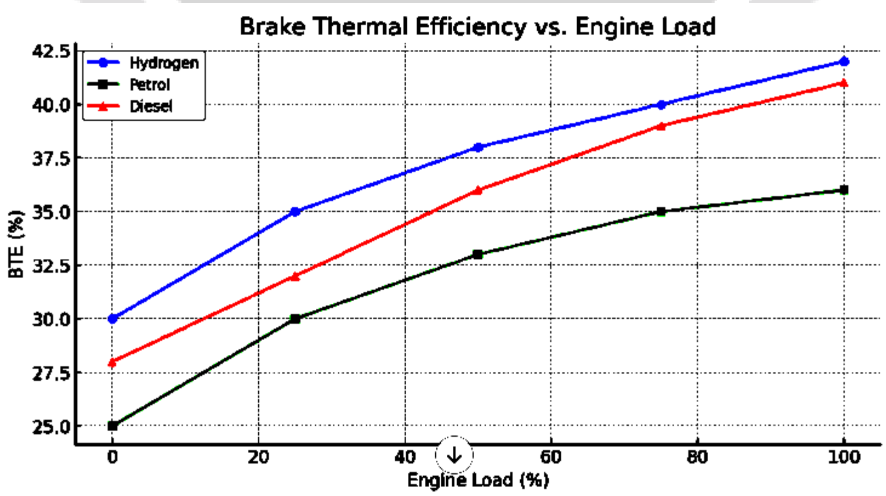

Chart -1: Brake Thermal Efficiency vs. Engine Load

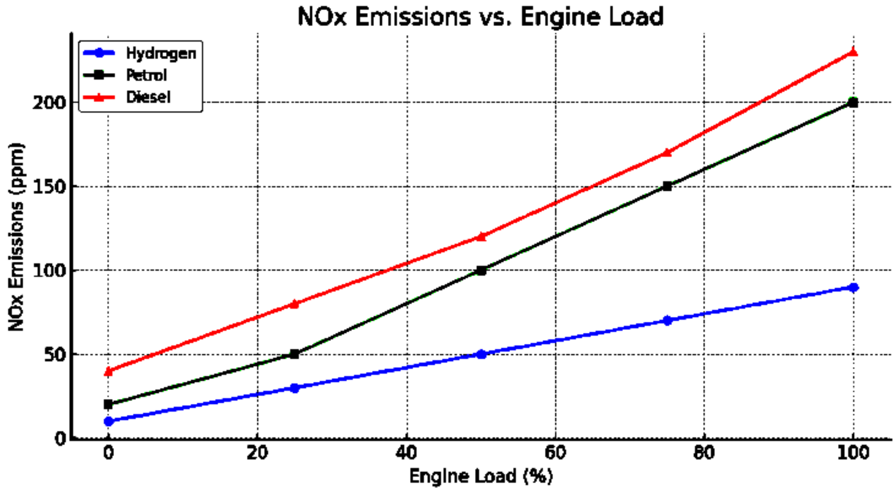

Chart -2: NO_x Emissions vs. Engine Load

5. CONCLUSION

- Hydrogen demonstrates superior combustion characteristics and efficiency compared to petrol and diesel.
- Significant reductions in CO, CO_2, and HC emissions make hydrogen an environmentally friendly fuel.
- High NO_x emissions remain a challenge and require mitigation strategies such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR).
- Hydrogen has the potential to replace conventional fuels in IC engines, contributing to a sustainable energy future.

6. REFERENCES

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