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Research Paper

RESEARCH PAPER ON HYDROGEN INTERNAL COMBUSTION ENGINE

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Abstract

Hydrogen Internal Combustion Engines (H_2 ICE) present a transitional yet promising pathway toward sustainable mobility by utilizing hydrogen as a clean alternative fuel. Unlike conventional fossil fuels, hydrogen combustion produces negligible carbon dioxide emissions, making it an attractive solution for reducing greenhouse gas footprints in transportation and stationary power generation. However, the unique properties of hydrogen—such as its wide flammability range, high diffusivity, and low ignition energy—pose challenges in engine design and operation. This paper investigates the combustion characteristics of hydrogen in spark-ignition and compression-ignition engines, focusing on flame speed, knock tendencies, and backfire risks. Advanced injection strategies, including port fuel injection and direct injection, are analyzed to optimize efficiency and minimize abnormal combustion. A critical issue addressed is the formation of nitrogen oxides (NOx), which can occur due to high flame temperatures despite hydrogen's carbon-free nature. Techniques such as lean-burn operation, exhaust gas recirculation (EGR), and catalytic after-treatment are discussed as effective NOx mitigation methods. Recent research, prototype developments, and industrial applications are highlighted, emphasizing hydrogen's role in bridging the gap between current internal combustion technologies and a carbon-neutral future. Ultimately, H_2 ICE offers a practical and impactful solution in the global pursuit of sustainable energy systems.

Keywords : Hydrogen Fuel ;Alternate Energy ; Engine Performance ; Zero Emission ; Clean Fuel

Introduction

In the second half of the twentieth century, the overall global population had begun to increase [1]. This has led to the phenomenal rise in demand for conventional fuels. By 2030 the global population will be 8 billion [2] and their energy demand will be around 700 EJ/year[3]. Hydrogen as a fuel has great potential as for new generation internal combustion (IC)engines with reduced emissions and improved thermal efficiency[4]. The major challenges to the automotive industry are to develop power trains which deliver lower CO_2 emissions and take care of the environment. The internal combustion engines powered by hydrogen fuel needs to be developed either as a sole power source or in addition to other fuels such as hybrid or range extenders. Today's world is meeting its energy needs by using primary fossil fuels which will be depleted shortly. The cost of fuel is increasing due to increase in demand and improvement in the economic condition of every individual. The increase in the use of fossil fuels is increasing the CO_2 emissions which are the main reason for global warming and air pollution. The energy security and global warming are the drivers of research, development and demonstration of different alternative fuel vehicles. Most of the government's i.e.US, Europe, Japan and India have formulated long term and short term energy security plan and allocated the fund for research on hydrogen fuel in internal combustion engines. These governments release fund for hydrogen demonstration projects such as Hydrogen vehicles with internal combustion engines (H2ICE), Hydrogen fuel cell vehicles (H2FCV)

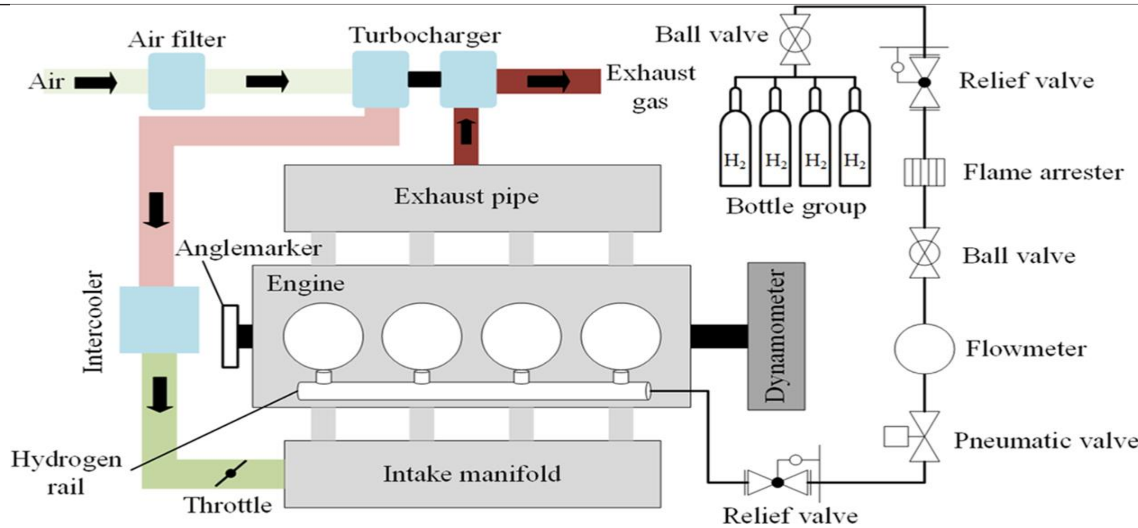
Today the world's energy demand depends on primary fossil fuels which are decreasing day by day [15]. Due to the exhaustible nature of fossil fuels and their prices are always fluctuating hence second thought is given for utilisation of alternative fuels in internal combustion engines. Global warming and local hot spots are also the major concern of fossil fuels. Research on hydrogen engine and the vehicle has been started since 1820 by Cecil [16]. Hydrogen can be used in an internal combustion engine as [17] dedicated fuel, bi-fuel or dual-fuel operation [12]. Many research institutions and government agencies started research base projects; some of them have demonstrated the use of hydrogen in an internal combustion engine as an effective and safe way. Hydrogen has no carbon bond hence no production of CO and CO_2 emissions. When burning of hydrogen in internal combustion engine, NOx is formed still it is the cleanest fuel. The recent literature review on hydrogen usage on IC engine by Dinçer et al [18] revealed that the amount of hydrogen added to the fuel system increased the engine power and torque almost like petrol engines, while they are decreased on LPG and diesel engines.

characteristics	**hydrogen**	**gasoline**	**methane**
lower calorific value (MJ/kg)	**120**	**44.8**	**50**
flame propagation speed (m/s)	**2.63–3.25**	**0.3–0.5**	**0.34–0.37**
minimum ignition energy (mJ)	**0.02**	**0.24**	**0.29**
flammability range (volume fraction in air, %)	**4–75**	**1.3–7.1**	**5–15**
stoichiometric air-to-fuel ratio	**34.4**	**14.7**	**17.3**
auto-ignition temperature (K)	**858**	**503–753**	**810**

The combustion process directly determines the thermal efficiency of an engine, and the formation of the mixture plays a crucial role in combustion. (7) Therefore, similar to traditional internal combustion engines, (8−10) the study of mixture formation is also an important aspect of hydrogen internal combustion engines (HICE). The excess air coefficient has a significant impact on the combustion rate and NOx emissions in HICE. During lean combustion, the combustion rate is much lower compared to the equivalence ratio. Therefore, it is vital to implement a control strategy in hydrogen ICE that increases the combustion rate during lean combustion to achieve higher thermal efficiency while reducing the combustion rate during equivalent combustion to minimize combustion roughness and NOx emissions. Consequently, a reasonable injection strategy holds immense significance in effectively controlling the combustion process in hydrogen ICE

Methodology :

The hydrogen engine utilized in this paper has been modified from a 4-cylinder gasoline direct injection engine. A hydrogen rail and hydrogen injectors were installed for hydrogen injecting. The main parameters of the engine are listed in Table 2. The experimental setup comprises an engine system, fuel supply system, measurement, and control system. A schematic diagram illustrating the layout of the test bench is depicted in Figure 1.



parameters	specification
type	inline, 4-stroke, turbocharge
number of cylinders	4
bore (mm)	83
stroke (mm)	92
displacement (L)	1.99
compression ratio	11.2
injection type	HDI
injection pressure (bar)	16–100

Hydrogen is supplied from a group of hydrogen gas bottles (40 L × 16, 10 MPa). The hydrogen supply system includes pipelines, ball valves, dual-stage pressure regulators, flame arresters, a hydrogen flow meter (Rheonik, RHM03L, accuracy: 0.98%), pneumatic valves, a hydrogen rail, and hydrogen injectors. The output torque is measured by a 160 kW eddy current dynamometer (CW160, speed accuracy ±1 rpm, Torque resolution: 0.1 N·m). The cylinder pressure is measured using pressure sensors (Kistler, 6115CF, linearity: ±0.13% FSO), and the crank angle signal is obtained through an angle marker (AVL, 365C). These signals are acquired and analyzed by a combustion analyzer (AVL, INDICOM 602). Emissions are measured using a motor exhaust gas analyzer (HORIBA, MEXA-7400DEGR).

Experimental Method :

In this study, experimental studies were conducted to investigate the influences of different injection strategies on the combustion performance of hydrogen engines. The specific parameters for each study are listed in Table 3. The first two sets of experiments focused on studying the effects of different timings and pressure of injection on the combustion performance of hydrogen engines under different λ. The third set of experiments explored the impact of the dual injection strategy, specifically the Secondary End of Injection (SEOI) and Secondary Injection Proportion (SIP), on combustion performance under different λ values. Under heavy loads, the injection pulse is relatively wide due to low injection pressure, and this wide injection pulse results in a restricted range for adjusting injection strategies. Besides, because the combustion rate is already quite fast at heavy loads, the improvement of combustion performance by optimizing the injection strategy is limited. Therefore, the experimental operating conditions primarily range from 2 to 8 bar in Brake Mean Effective Pressure (BMEP) and the engine speed is fixed at 1200 rpm. CA10, CA50, and CA90 denote the crank angles corresponding to the cumulative heat release reaching 10, 50, and 90% of the overall heat release, respectively. In the paper, the combustion duration is defined as the crank angle interval between CA10 and CA90, and the ignition delay is defined as the crank angle interval between the spark timing and CA10. CA50 represents the combustion phase, which is used to determine whether the combustion phase is appropriate. For the safety and validity of test results, the COV of BMEP was controlled to within 3% during the experiment. If the COV went beyond 3% under an injection strategy, that injection strategy was considered inappropriate, and the result was not recorded.

Table 3. Main Study Parameters of the Experiment

no.	**λ**	**injection pressure (bar)**	**SOI (CA BTDC)**	**SEOI (CA BTDC)**	**SIP (%)**
1	1.0/1.5/2.0	50	30–200		0
2	1.0/1.5/2.0	20/50/80	180		0
3	1.0–2.3	50	180	20–100	10/30/50

Results and Discussion :

◆ Results

- Performance Improvements:
    - Hydrogen addition to IC engines increases power and torque to levels comparable with petrol engines.
    - In LPG and diesel engines, blending hydrogen reduces performance slightly but improves emissions.
- Emission Characteristics:
    - Zero CO and CO_2 emissions due to absence of carbon in hydrogen.
    - NOx emissions are formed because of high flame temperatures, but still significantly lower than conventional fuels.
- Combustion Behavior:
    - High octane rating allows operation near knock limit.
    - Late ignition timing required → produces higher exhaust gas temperatures.
- Engine Modifications:
    - Hard-anodized piston rings and optimized ring pack reduce blow-by and oil consumption.
    - Cooling systems must be enhanced to handle high thermal loads.

Discussion

- Environmental Impact:
    - Hydrogen IC engines directly address global warming concerns by eliminating CO_2 emissions.
    - NOx remains a challenge, requiring advanced after-treatment systems (EGR, catalytic converters).
- Energy Security:

  - Hydrogen reduces dependence on fossil fuels, aligning with government energy security plans.
  - Demonstration projects (H_2ICE, H_2FCV) highlight global commitment to hydrogen adoption.
- Technical Challenges:
  - Storage and distribution of hydrogen remain critical barriers.
  - Engine design must balance efficiency, safety, and durability under high thermal loads.
- Future Outlook:
  - Hydrogen IC engines serve as a bridge technology between fossil fuel engines and hydrogen fuel cells.
  - With continued R&D, hydrogen can become a mainstream fuel for sustainable mobility.

Conclusions :

This paper investigates the impacts of various injection strategies on the combustion characteristics of HDI engines through experimental analysis. The key findings can be summarized as follows:

- For BMEP of 2 and 5 bar, properly delaying injection can improve thermal efficiency by up to 2.6% because of reducing the negative work of compression stroke and heat transfer loss. However, premature SOI decreases thermal efficiency due to increased heat transfer losses resulting from higher hydrogen concentration near the cylinder wall. For equivalent combustion, NOx emissions can be reduced from 4574 to 560 ppm, nearly 88%. But the effect of SOI on NOx of lean combustion is limited.
- Since gaseous hydrogen has no atomization process and has a strong diffusion capacity, hydrogen injection pressure has a slight influence on the combustion rate and emissions. Therefore, blindly increasing the injection pressure is not meaningful and may result in a reduced cruising range due to decreased available hydrogen. However, when the injection pressure is increased from 2 to 8 MPa, the injection pulse width decreases by approximately 75%, respectively, which allows for greater flexibility in delaying the injection timing to achieve higher thermal efficiency and lower pre-ignition probabilities.
- Delaying SEOI for dual injection, BTE is improved by about 1.5 and 0.6% for leaner cases ($\lambda = 1.8$ and 2.3) and richer cases ($\lambda = 1.5$ and 1.0), respectively, and NOx of richer cases is reduced by more than 47%. With the delay of SEOI, the movement of secondary injection jet transiting from a clockwise motion guided by the cylinder wall to no-guide path and finally to a counterclockwise motion guided by the piston. Therefore, combustion duration and ignition delay first decrease, then increase, and finally decrease again with SEOI delaying.
- Increasing the Secondary Injection Proportion (SIP) has a minimal impact on improving BTE, with an increase of no more than 1%. For richer cases ($\lambda = 1.5$ and 1.0), increasing SIP can significantly reduce NOx emissions by over 43%, but combustion rate and cylinder pressure change slightly. For ultralean ($\lambda = 2.3$), the peak HRR increases nearly 14% and combustion duration shortens about 19% when SIP increases from 0 to 30%. However, NOx changes negligibly with the increase of SIP

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