www.ijprems.com
editor@ijprems.com

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 01, January 2025, pp : 1781-1793

e-ISSN : 2583-1062
Impact Factor : 7.001

# HYDROGEN AS A FUEL FOR INTERNAL COMBUSTION ENGINES: COMBUSTION CHARACTERISTICS, CHALLENGES, TECHNOLOGICAL ADVANCEMENTS, AND PRELIMINARY RESULTS

**Amr Abbass[1]**

[1]Institute/Organization: Alexandria University, Egypt

DOI: https://www.doi.org/10.58257/IJPREMS38416

## ABSTRACT

Hydrogen is a progressively feasible alternative fuel for internal combustion engines (ICEs), providing improved efficiency and diminished environmental effect. This study examines the combustion properties of hydrogen in internal combustion engines relative to traditional fuels including gasoline, methane, and iso-octane. Hydrogen's exceptional energy density (120 MJ/kg), little ignition energy (0.02 mJ), and elevated flame speed (2.4 m/s) enhance its efficiency and quick combustion characteristics. Nonetheless, issues like as pre-ignition, backfire, and elevated NOx emissions need sophisticated combustion management techniques, including lean-burn operation, exhaust gas recirculation (EGR), and water injection. The principal attributes of hydrogen combustion are examined, emphasizing its extensive flammability range (4%-75%), high autoignition temperature (585°C), and significant diffusivity, which promote effective air-fuel mixing. Hydrogen-powered spark ignition (SI) and compression ignition (CI) engines are assessed regarding performance, efficiency, and emissions. This analysis explores the function of hydrogen in advanced combustion techniques, specifically Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RCCI), highlighting its capacity to diminish particulate matter (PM) and nitrogen oxides (NOx) emissions while preserving elevated thermal efficiency. The research examines ignition delay, flame propagation, and knock resistance through computational simulations utilizing Python and Cantera. Research demonstrates that hydrogen engines possess elevated thermal efficiency; yet, they necessitate meticulous regulation of ignition timing and air-fuel ratio to prevent atypical combustion occurrences. The amalgamation of direct injection and turbocharging technologies enhances hydrogen combustion stability and volumetric efficiency. Comparative assessments of hydrogen-fueled engines against conventional and alternative fuels highlight the trade-offs among efficiency, emissions, and operability. Hydrogen-powered internal combustion engines present viable solutions for sustainable energy transition, especially in heavy-duty transportation and stationary power generation. Continued progress in hydrogen storage, fuel injection technology, and NOx reduction methods will improve the viability of hydrogen as a primary fuel for future internal combustion engines.

## 1. INTRODUCTION

Hydrogen: An Efficient and Eco-Friendly Fuel for Internal Combustion Engines Hydrogen is a potential choice for the desired fuel of future energy systems. This feature allows it to be viewed favorably as an energy carrier. Hydrogen combustion is widely recognized for producing just water vapor, with negligible carbon dioxide emissions. Fuel efficiency varies markedly due to the differing combustion characteristics of hydrogen and gasoline. One reason is that hydrogen possesses a significantly higher heating value (120 MJ/kg), but gasoline has a considerably lower energy density (44 MJ/kg). Consequently, hydrogen exhibits significantly more energy output upon combustion than gasoline, yielding 120 MJ/kg of lower heating value, whereas gasoline produces just 44 MJ/kg. Hydrogen gas is more easily combustible than gasoline, possessing an ignition energy of approximately 0.02 mJ, compared to gasoline's 0.24 mJ. The significant differences in flame velocity of hydrogen (2.4 m/s) compared to gasoline (0.37 m/s) contribute to this phenomenon. Moreover, automobile gasoline has a restricted flammability range (14%-76%) compared to hydrogen (4%-75%). The notable statistics indicate that hydrogen gas's auto-ignition temperature is higher than gasoline's, with values of 585°C compared to 450°C, respectively. These qualities reinforce the perception of hydrogen as an efficient and environmentally beneficial fuel (Potential of hydrogen fuelled IC engine to achieve the future performance and emission norms, 2015).

**Table 1** Comparison of Hydrogen Combustion Characteristics to Gasoline (Recent progress in the use of hydrogen as a fuel for internal combustion engines, 2014).

| Property | Hydrogen | Gasoline |
|---|---|---|
| Lower Heating Value (LHV) | 120 MJ/kg | 44 MJ/kg |
| Ignition Energy | 0.02 mJ | 0.24 mJ |

| | | |
|---|---|---|
| Flame Speed | 2.4 m/s | 0.37 m/s |
| Flammability Range (vol %) | 4% - 75% | 1.4% - 7.6% |
| Autoignition Temperature | 585°C | 450°C |

**Tabel 2** Comparison of Hydrogen Combustion Characteristics to other Fuels (Recent progress in the use of hydrogen as a fuel for internal combustion engines, 2014)

| Property | Hydrogen | Methane | Iso-Octane |
|---|---|---|---|
| Lower heating value (MJ/kg) | 120 | 50 | 44.3 |
| Higher heating value (MJ/kg) | 142 | 55.5 | 47.8 |
| Lower heating value (MJ/Nm³) | 10 | 33 | 30656 |
| Higher heating value (MJ/Nm³) | 12 | 37 | 33078 |
| Molecular weight (g/mol) | 2.016 | 16.043 | 114.236 |
| Density (kg/m³) | 0.08 | 0.67 | 692 |
| Ratio of specific heats (γ) | 1.405 | 1.304 | 1.047 |
| Flammability limits in air (%) | 4–75 | 5–15 | 1.1–6 |
| Stoichiometric air-to-fuel ratio (kg/kg) | 34.2 | 17.1 | 15 |
| Minimum ignition energy (mJ) | 0.02 | 0.28 | 0.28 |
| Minimum quenching distance (mm) | 0.64 | 2.03 | 3.5 |

## 2. HYDROGEN ENGINE COMBUSTION DETAILS & CRITERIA

**2.1 Major Concepts and Important Characteristics of Hydrogen Combustion** (Introduction to Application of Clean Fuels in Combustion Engines, 2022) **:**

- High Flammability Extremes: Hydrogen ignition can occur at a wide range of fuel-to-air ratios, including fuel-lacking mixtures, so its combustion can occur quickly. This fuel-lacking mixture has limited output power, decreased the combustion temperature and lowered nitrogen oxide emissions while increasing fuel efficiency.
- Small Ignition Energy Requirement: Lean mixtures are complex to ignite. However, flashbacks and premature ignition are more likely because hot spots can trigger the mixture due to insufficient ignition energy.
- Low Flashing Distance: The distance from the flame to the cylinder wall is less for hydrogen engines, thus increasing the chances of backfire.
- Elevated Autoignition Temperature: Hydrogen's elevated autoignition temperature facilitates increased compression ratios, improving engine efficiency. - This thermal property allows hydrogen engines to employ higher compression ratios without the risk of premature igniting, rendering hydrogen inappropriate for diesel-type compression engines as the ignition temperature will be very high.
- High Flame Speed: Unlike gasoline engines, hydrogen engines have more incredible flame speed, which allows them to function at maximum operational efficiencies, particularly in thermodynamic power cycles.
- High Diffusivity Given its high diffusivity, hydrogen can mix uniformly with exhaust gas air, aiding in homogenizing the mixture. This improves combustion safety risks by quickly scattering out any hydrogen leaks.
- Low Density: Hydrogen's energy storage capacity is relatively low because of its low density, which limits the miles per gallon the hydrogen-air mixture can drive and the total power output.
- Adiabatic Flame Temperature: Adopting hydrogen mixtures without any control means operating with a flame temperature of 2390 K, thereby increasing NOx gases that require lean-burn or exhaust gas recirculation (EGR) to control.
- The combustion temperature of hydrogen is significantly elevated, reaching around 2318-3200 K under stoichiometric combustion circumstances, which exceeds the NOx production temperature of around 1800 K. Nitrogen oxides are harmful pollutants linked to the formation of smog, acid rain, and detrimental impacts on human health. Consequently, in investigating the energy potential of hydrogen, it is essential to minimize the production of NOx resulting from hydrogen combustion.
- The Low-Temperature Combustion (LTC) method can diminish NOx and Particulate Matter (PM) emissions by maintaining combustion temperatures within safe parameters. The extensive hydrogen concentration range, with lower and upper limits of 4% and about 75%, respectively, renders LTC regimes advantageous for hydrogen

combustion, as it can ignite in extremely lean mixes at reduced temperatures. However, achieving precise control over air-fuel mixing, ignition events, and combustion phases is essential, rendering hydrogen engines more technologically difficult than hydrocarbon-based engines.

- Hydrogen exhibits unique combustion properties compared to traditional fuels such as gasoline or diesel. The stoichiometric air-fuel ratio (AFR) for hydrogen is around 34.33:1, signifying that 34.33 kilograms of air are required to combust 1 kilogram of hydrogen. This represents a significant gain relative to the gasoline combustion efficiency at the stoichiometric ratio of 14.7:1. The considerable disparity in the AFR factor necessitates that hydrogen combustion systems augment airflow rates and the dimensions of the intake systems to sustain sufficient oxygen levels.
- The laminar flame speed of hydrogen is significantly greater than gasoline's. At stoichiometric ratios, the laminar flame speeds of hydrogen range from 1.85 m/s to 2.85 m/s, while the flame speed of gasoline is 0.37 m/s. One consequence of this disparity is that during combustion, the velocity of the flame front significantly increases, potentially leading to elevated cylinder pressure in a brief period. A swift increase in pressure is a mechanical design difficulty in an engine, as it often leads to engine knocking, which arises from unregulated combustion processes that jeopardize the engine's integrity.
- The combustion behavior of hydrogen is further exacerbated by its ignition energy, which is less than 0.02 mJ, significantly lower than that of other fuels. The low ignition energy increases the possibility of delayed explosions or pre-ignition, occurring when the air-fuel mixture ignites due to hot patches in the combustion chamber before the usual combustion phase. After the engines have been deactivated, hot spots may also arise from residual heat in engine components, such as the spark plug or exhaust valves. Pre-ignition establishes conditions conducive to knocking, which can harm the engine's internal components. Furthermore, hydrogen possesses a broad flammable range (4% – 75% in air), allowing its utilization in lean burn scenarios to improve combustion efficiency and reduce NOx emissions by decreasing peak combustion temperatures.

**2.2 Key Equations For Hydrogen Combustion Engine** (S. Molina, 2023)

**Stoichiometric Combustion of Hydrogen:**

Reaction:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (1)$$

Moles of hydrogen $(H_2)$ needed for complete combustion: 2 moles

Moles of oxygen $(O_2)$ needed for complete combustion: 1 mole

Air composition requires 4.762 moles of air per mole of $O_2$.

**Mass-based A/F ratio:**

$$\frac{A}{F\ \text{ratio}} = \frac{\text{mass of air}}{\text{mass of fuel}} = \frac{137.33\ \text{g}}{4\ \text{g}} = 34.33:1 \qquad (2)$$

**Volume-based A/F ratio:**

$$\frac{A}{F\ \text{ratio}} = \frac{\text{moles of air}}{\text{moles of fuel}} = \frac{4.762}{2} = 2.4:1 \qquad (3)$$

**Percentage of hydrogen in the chamber at stoichiometric conditions:**

$$\%H_2 = \frac{\text{volume of } H_2}{\text{total volume}} = \frac{2}{4.762 + 2} = 29.6\% \qquad (4)$$

**Compression Ratio and Temperature Rise (Autoignition Limitation):**

The temperature increase during compression must not surpass hydrogen's autoignition temperature in spark-ignited engines and should achieve autoignition in compression engines, which is the primary concern. Challenge for Hydrogen compression Ignited Engines:

$$T_2 = T_1 \cdot \left(\frac{V_1}{V_2}\right)^{\gamma - 1} \qquad (5)$$

Where $T_1$ is the initial temperature, $T_2$ is the final temperature, $V_1/V_2$ is the compression ratio, and $\gamma$ is the specific heat ratio.

**Equivalence Ratio ( Φ ):**

Equivalence ratio for air-fuel ratios, where a stoichiometric mixture has $\Phi = 1$ :

$$\Phi = \frac{\text{stoichiometric A/F ratio}}{\text{actual A/F ratio}} \qquad (6)$$

**Thermal Efficiency**

Theoretical Thermal Efficiency, Based on the compression ratio and specific heat ratio (γ).

Equation:

$$\eta_{th} = 1 - \left(\frac{1}{\text{Compression Ratio}}\right)^{\gamma-1} \quad (7)$$

Specific Heat Ratio: Hydrogen's $\gamma = 1.4$, higher than gasoline's 1.1, leading to higher efficiency.

Higher Compression Ratios: Allowed due to hydrogen's lower knock tendency.

**Flame characteristics define hydrogen combustion** (A. Keromnes, 2013), each influencing engine performance and emissions. Understanding the flames generated by hydrogen and their relationship with combustion is crucial for improving the complexity of internal combustion engines and their operating techniques for combustion management.

$$E_{ign} \approx C \cdot V \cdot \rho \cdot S_L \cdot \left(\frac{T_f}{T_u} - 1\right)$$

$E_{ign:}$ Ignition energy, C : Constant, V : Volume, ρ : Density, $S_L$ : Flame speed, $T_f$ : Flame temperature, $T_u$ : Unburned gas temperature.

$$k = A\exp\left(\frac{E_0}{RT}\right)$$

k : Reaction rate constant, A : Pre-exponential factor, $E_a$ : Activation energy, R : Gas constant. T : Temperature

$$T_f = T_u + \frac{\Delta H_r}{C_p(1+\varphi)}$$

$T_f$ : Flame temperature, $T_{in}$ : Unburned gas temperature, $\Delta H_c$ : Heat of combustion, φ : Equivalence ratio, $C_p$ : Specific heat

$$T_{anto} \approx \frac{E}{R}\ln\left(\frac{A}{rate}\right)$$

$T_{auto:}$ : Autoignition temperature, $E_a$ : Activation energy, R : Gas constant, A : Pre-exponential factor, rate: Reaction rate

$$Le = \frac{a}{D}$$

Le: Lewis number, α : Thermal diffusivity, D : Diffusion coefficient

$$D \approx \sqrt{\frac{\alpha RT}{M}} + u_f$$

D : Detonation velocity, γ : Adiabatic index, R : Gas constant, T : Temperature, M : Molecular weight, $u_f$ : Flame speed

$$D = \sqrt{\frac{\lambda RT}{M}} + \text{ flame speed}$$

D : Detonation velocity, γ : Adiabatic index R : Gas constant, T : Temperature, M : Molecular weight, flame speed: Flame velocity

A laminar premixed flame arises when the fuel and air are well combined before ignition. In this regime, it propagates as a planar wave within the gaseous mixture at a constant, well-defined velocity. The capacity of hydrogen to attain elevated laminar flame speeds renders it particularly attractive for laminar combustion under suitable operational parameters. The flame front is very predictable in laminar combustion due to its uniform surface. This is beneficial since it facilitates the intake and exhaust cycles of the engine, where combustion efficiency and the emission of dangerous gases are paramount. The rapid expansion of the flame presents complications, including issues of pre-ignition and backfire, mainly observed in high compression ratio engines.

In laminar premixed hydrogen flames, the relative flame thickness is considered minimal compared to the depth of hydrogen flame stabilization due to the high diffusion rate of hydrogen gas and the rapid reaction rate. The thermal thickness of a hydrogen flame can be expressed as follows:

$$\delta_T = \frac{\alpha}{S_L}$$

Where αIs the thermal diffusivity of the fuel-air mixture and $S_L$Is the laminar flame speed. Due to the slender flame front, laminar hydrogen flames are susceptible to many instabilities, particularly under elevated pressures and temperatures.

Flame Laminar Speed of Hydrogen:

$$S_L = \sqrt{\frac{2 \cdot D \cdot k}{\rho_u}}$$

Where $S_L$ is Laminar flame speed ( m/s ), D is diffusivity, kIs the reaction rate constant, and $\rho_u$Is unburned gas density.

In actual engine designs, flames exhibit turbulence rather than laminar flow. Turbulent flames occur when the mixing conditions are non-axial, disrupting the flame front by the swirling motion characteristic of fire. The turbulent flow is quantified by the Reynolds number (Re), which represents the ratio of inertial to viscous forces in the flow, among other factors. Turbulent combustion regimes typically produce less uniform flame fronts, increasing the combustion rate and enhancing fuel-air interaction.

Regulating turbulence in hydrogen engines is more challenging than managing laminar flames due to the interplay between turbulence and combustion processes. The flame front propagation in turbulent combustion is non-uniform and fluctuates based on local turbulence intensity, fuel concentration, and temperature differentials. Turbulence in natural gas-fueled engines may improve combustion but can also lead to adverse phenomena such as knocking or detonation.

$$S_T = S_L \cdot \left(1 + C_T \cdot \frac{u'}{S_L}\right)$$

where $C_T$Is a constant that depends on the specific combustion system. Regulating the turbulent flame velocity is crucial for ensuring stable combustion and averting excessive pressure increase rates in hydrogen engines. The turbulent flame speed ($S_T$) is often modeled as a function of the laminar flame speed and the turbulence intensity ($u'$) Therefore, regulating elevated turbulent flame speeds is essential for hydrogen engines to maintain stability in combustion mode and dynamics by averting rapid pressure increases. Flashback and backfire are defined as two abnormal behaviors of flame propagation, which may appear in hydrogen engines due to the hydrogen fuel's high combustion velocity and the low energy rate required to ignite it. For flashback, it is the phenomenon where the flame starts moving in the opposite direction, in this case toward the intake manifold, where it can ignite the blended mixture of air and fuel. Backfire, however, involves the ignition of the blended mixture, but the intake valve has not yet closed, and therefore, gas enters the combustion chamber. Both phenomena potentially damage the engine and must be controlled by optimizing the air-fuel ratio, ignition timing, and fuel injection strategy.

**2.3 Main Characteristics of Combustion in Hydrogen Engines** (Performance Estimation of a Downsized SI Engine Running with Hydrogen, 2022)**:**

- Pre-Ignition in Hydrogen Engines Principal Concern: In this context, premature ignition is more prevalent in hydrogen combustors due to hydrogen's low ignition energy, extensive flammability range, and short quenching distance. Pre-ignition leads to suboptimal performance and erratic engine operation; an air-fuel mixture near the fuel intake valve can cause a backfire if it take place. Areas of High Activity: Hot Spot sources encompass spark plugs, exhaust valves, deposits, and the pyrolysis of oil present in the combustion chamber. The overlap of the intake and exhaust valves may facilitate the combustion of the exposed air-fuel combination in the intake manifolds, leading to backfire.
- Central (Carbureted) Injection is the easiest method for lowering hydrogen pressure, but it's associated with pre-ignition and backfire. Port Injection reduces pre-ignited gas and prevents ignition problems. Direct Injection injects hydrogen gas after shutting the intake valve, eliminating the risk of backfiring and adding over 20% power to gas engines. Direct fuel and air injection has drawbacks like poor mixture and higher NOx pollutants, which mandate the use of exhaust gas recirculation (EGR) and water injection to manage NOx levels.

**2.4 Hydrogen-Powered Spark Ignition Engines** (Hydrogen as a spark ignition engine fuel, 2003)

- Hydrogen-powered SI engines can help reduce carbon emissions in heavy-duty sectors by combining advanced fuel injection methods and combustion temperature regulation with hydrogen-enhanced properties. This allows hydrogen engines to compete with electric engines in areas where battery-electric solutions aren't possible. R&D is focused on integrating these strategies to enhance efficiency and emission reduction. However, hydrogen engines face challenges during combustion, including backfire and surface ignition.

**2.5 Abnormal Combustion and Challenges in spark ignited Hydrogen Engines** (Performance Estimation of a Downsized SI Engine Running with Hydrogen, 2022)**.**

- Hydrogen fuel offers advantages in SI engine performance due to its unique combustion characteristics, including broader flammability limitations and higher ignition temperatures, but it also raises concerns like backfire and surface ignition.

- Backfire and Surface Ignition: The combustion of the hydrogen and air combination in the intake manifold causes the flame to propagate towards the rear, potentially damaging the intake system and diminishing power density.
- Surface Ignition: This phenomenon occurs when heated surfaces, such as spark plugs or valve deposits, induce independent ignition with minimal energy requirements and a reduced quenching distance for hydrogen, enabling flames near the cylinder wall surfaces to persist in combustion.
- Effectiveness Heat Loss Variation: Optically, methane seems to exhibit lesser effective heat loss with an increase in load, but on the contrary, hydrogen stands at 24% effective heat loss at a low load and increases to 37% at a high load. In practice, hydrogen engines operate at higher loads for extended periods and dissipate more effective heat due to larger surface areas exposed to wall flame. As such, persistent temperatures are near combustion.
- Impact on Efficiency: Allowing excessive heat losses can lower the thermal efficiency value of holistic analysis on the viability of hydrogen engines. Therefore, it would require additional and more effective cooling management, which internally may shift lean operations aiming at high efficiency but then sacrificing performance expectancy.
- Cylinder walls in hydrogen engines are hotter and radiate more energy because of the fuel's inherent flame temperature and short quenching distance. This also leads to excessive heat transfer to the cylinder wall. Such a temperature should always remain under control because it enhances the formation of NOx, otherwise impacting efficiency and NOx emissions in equal measures.
- Resolutions: Cold-rated and non-platinized spark plugs prevent platinum-induced catalytic ignition. Injection phasing regulates wall temperatures and minimizes hydrogen in the intake system. Oil control minimizes oil droplets, enhancing efficiency in hydrogen spark-ignited engines. Combining heat and power improves efficiency.
- Emissions in hydrogen spark-ignited engines Hydrogen combustion in SI engines produces water vapor with low carbon emissions, but NOx emissions remain a critical issue due to high combustion temperatures. Hydrogen engines can use lean combustion and exhaust gas recirculation (EGR) strategies to control NOx emissions. Lean combustion allows hydrogen engines to maintain combustion temperatures below NOx formation thresholds, while EGR reduces peak combustion temperatures. Aftertreatment systems for NOx reduction include two-way catalysts (TWC) and selective catalytic reduction (SCR) systems. TWC can achieve NOx conversion efficiencies over 99%, especially at exhaust temperatures above 400°C. SCR systems can be urea-based or hydrogen-based, with hydrogen-based systems having lower conversion efficiency. Real-world driving emissions (RDE) standards require NOx control systems to function effectively during rapid load changes and transient operation.
- Elevating power density frequently results in elevated in-cylinder temperatures, increasing NOx emissions. This trade-off necessitates a balance between substantial power production and efficient NOx control.
- Efficiency against NOx Emissions:Postponing ignition timing to diminish NOx emissions might decrease efficiency by lowering peak cylinder pressures. Stratified combustion may enhance efficiency; however, it often results in elevated NOx emissions due to localized high temperatures.

**2.6 Special Components of a Hydrogen Engine Ignited by Spark**

- BorgWarner has developed a Direct Injection Injector for hydrogen engines, which supports CO2-free mobility and offers low total cost of ownership due to optimized energy efficiency, payload capacity, and short refueling time. The injectors function at 20-40 bar, avert backfire, and achieve high volumetric efficiency. The valve design enhances hydrogen sealing, facilitating elevated flow rates and adaptable spray, potentially reducing NOx emissions by up to 50%. The company works with OEMs in all vehicle segments and can supply individual components or complete turnkey solutions. Challenges include regulating moisture in EGR systems and balancing lubricants and sensors.
- Hydrogen SI engine research has evolved from feasibility to sophisticated prototype designs for heavy-duty applications. Advances in turbocharging, direct injection, hydrogen storage, and NOx after-treatment have led to heavy-duty hydrogen engines targeting performance metrics typical of diesel engines. Deutz AG developed a hydrogen engine for mobile machinery, MAN Truck & Bus SE developed a hydrogen engine for long-haul trucks, and Cummins focuses on converting existing diesel engines to hydrogen.
- Hydrogen engines are increasingly considered for applications in sectors like off-road and non-road mobile machinery, heavy-duty trucking, and long-haul transport. They offer better thermal management, durability, and efficiency than fuel cells, making them ideal for high-load applications and dusty environments. Additionally, hydrogen engines are gaining attention for their robustness and ease of refueling, making them suitable for industrial, off-road, and remote operations.
  These engines are also gaining attention for their durability and environmental sensitivity.

**2.7 Hydrogen Compression Ignition Engines** (Hydrogen Compression Ignition Engines, 2023)

- Compression ignition (CI) engines, invented by Rudolf Diesel, are known for their high fuel efficiency and compression ratios. Early hydrogen combustion engines faced challenges due to high autoignition temperature and detonation. A 1936 study by the National Advisory Committee for Aeronautics showed hydrogen-air mixtures could improve brake thermal efficiency by up to 19%. The environmental regulations have renewed interest in hydrogen CI engines, with research focusing on engine design modifications, hydrogen as a primary or auxiliary fuel, and combustion challenges.
- Hydrogen CI engines face challenges due to low ignition energy, high ignition temperature, and rapid burn rate. Early research focused on reducing fuel storage weight with hydrogen's high energy density. Strategies include elevated intake air temperatures, high compression ratios, glow plug ignition assistance, and hybrid approaches. Modern approaches blend hydrogen with a primary fuel.
- Hybrid hydrogen CI engine technology offers promising solutions for sectors with limited storage space. It leverages hydrogen as a primary fuel with limited secondary fuel ignition.
- Hydrogen faces challenges in energy density, particularly low volumetric energy density, which affects storage and power output in applications like automotive and aerospace. Various methods have been developed to overcome this, but each has trade-offs. Hydrogen engines often experience abnormal combustion due to their high flammability and low ignition energy. Direct injection, controlled intake air temperature, and optimized injection timing can help mitigate these issues and enhance hydrogen's viability as a dual or primary fuel. Engine also face High NOx emissions, incomplete combustion, and safety. High combustion temperatures can improve engine efficiency but increase nitrogen oxides (NOx) formation. Factors influencing NOx formation include air-fuel mixture ratio, engine CR, speed, ignition timing, and thermal dilution. NOx control techniques like EGR or water injection can help dilute the intake charge and lower combustion temperatures. Incomplete combustion at low loads can result in a high proportion of unburned hydrogen in the exhaust, indicating poor combustion efficiency. Strategies to improve combustion efficiency include high EGR rates and adjusting liquid fuel injection timing.
- Hydrogen compression ignition design alterations and adjustments are needed to utilize hydrogen as a fuel in Compression Ignition engines. Port injection injects hydrogen into the combustion chamber during the intake stroke, allowing for better ventilation and reducing the risk of backfire and pre-ignition. This method is flexible in management and provides for a more manageable ratio of hydrogen-air. Manifold injection involves continuously injecting hydrogen without interruption, with Continuous Manifold Injection (CMI) and Timed Manifold Injection (TMI) being developed for enhanced control mechanisms.
- Direct injection, which occurs after the closure of the intake valve, prevents backfire by depriving the intake manifold of hydrogen. This method has two scenarios: immediately following the intake closure, characterized by low diaphragm tonicity (LPDI), or just before the conclusion of compression (HPDI). The implementation of HPDI significantly increases the complexity and expense of the system due to the use of high-pressure hydrogen injectors, which are meticulously regulated under severe conditions. Direct injection also faces challenges due to the diminished time available for thorough mixing, leading to incomplete combustion and significant cycle-to-cycle fluctuations.
- The development of direct injection fuel injectors is expensive due to hydrogen's higher diffusivity and lower lubricity, complicating the prevention of leakage and the endurance of the injector under high heat and pressure within a cylinder. While direct injection enhances power and volumetric efficiency and aids in combustion regulation, the shortcomings of the injectors must be resolved for compression ignition hydrogen engines to supplant port or manifold systems entirely.
- Additional valves on the engine head equipped with enhanced cooling systems can regulate the combustion rate to address hot spots. Optimized valve timing is necessary, mainly to avoid prolonged positive valve overlaps. Targeted valve angle kinetics can mitigate hot hydrogen scavenging and reduce the likelihood of backfiring. Variable valve timing can regulate exhaust and intake, facilitating enhanced scavenging that elevates the temperature of leftover gases, thereby mitigating aberrant combustion.
- Materials for valve seats and injectors are crucial, as excessive hydrogen can adversely affect performance by providing inadequate lubrication. Hardened or coated protective polymer or steel can withstand acceptable interactions with hydrogen, while a breathable area is crucial for these engines. Ashless lubricating oils are recommended for these engines to prevent stale combustion situations.
- The auto-ignition temperature of hydrogen is 858 K. Hence, combustion cannot depend exclusively on compression at the compression ratios employed in conventional diesel engines. Injecting a minimal amount of fuel at the onset of combustion enables the complete oxidation of hydrogen in compression ignition engines. The investigation of

hydrogen-diesel engines primarily focuses on various hydrogen substitution rates, utilizing hydrogen as the principal fuel and a minimal quantity of diesel as a supplementary fuel to facilitate combustion.

- Investigations on hydrogen-diesel engines indicate three data classifications concerning the quantity of hydrogen utilized. Minimal Substitution (≤ 10%): Certain research has investigated the utilization of hydrogen as a replacement for alternative fuels, enhancing engine efficiency; however, this occurs at a rate of nine percent or lower. Medium Substitution (10-60%): Consuming moderate hydrogen quantities enhances fuel efficiency and emission performance. However, it raises the likelihood of pre-ignition. High Substitution (≥90%): Hydrogen is the primary fuel for combustion, supplemented by minimal quantities of diesel to initiate the process. Dimitriou et al. required the utilization of merely 2% diesel and 98% hydrogen-fueled cars to achieve operational efficiency.
- Hydrogen fuel can be introduced via a port or manifold into the engine to achieve minimal emissions, enhancing fuel efficiency. Hydrogen can be directly injected, mitigating issues such as banging and pre-ignition. Increased hydrogen intake significantly enhances brake thermal efficiency while decreasing carbon monoxide and total hydrocarbon emissions. Nonetheless, there is a disadvantage of fourteen percent in volumetric efficiency, as elucidated by Sandalci and Karagöz, in addition to pre-ignition occurring when hydrogen is utilized in significant proportions.
- Tsujimura and Suzuki's heavy-duty engines show enhanced thermal efficiency under high loads, while fuel demand increases at low temperatures, diminishing hydrogen combustion in the diesel plume. Emission reductions include over 60% reduction in carbon monoxide and up to 63% reduction in particulate emissions. Smoke emissions decrease significantly during partial loads, with a 10-15% hydrogen substitution resulting in a 50% decrease. However, hydrogen-diesel engines are expected to produce higher NOx emissions due to self-ignited hydrogen instability and energy release that raises cylinder temperature.
- Biofuels offer potential solutions for aviation, marine, and heavy-duty vehicles but are not viable in short-term applications due to competition with food production. Hydrogen-biofuel dual-fuel engines offer a solution, transitioning biofuel utilization without halting production. Hydrogen-diesel emulsification performs similarly to diesel while generating lower CO2 levels. RME-enhanced biofuels reduce biomass emissions.
- Exhaust gas recirculation (EGR) is a method used to decrease NOx gas emissions in compression ignition engines (CI) by introducing carbon dioxide, nitrogen, and water vapor into the engine during combustion. Modern Common Rail Injectors provide greater control over injection timing, which can improve production and emissions but also increase emissions, particularly NOx. Injection tactics significantly influence performance, with increased diesel injection advance angle leading to increased NOx emissions.
- Compression Ratio (CR)The compression ratio (CR) is the primary design parameter for hydrogen-diesel dual-fuel engines, facilitating the prevention of knocking and preserving optimal performance. An elevation in the compression ratio (CR) is demonstrated to enhance engine brake thermal efficiency and power production, as reported (Miqdam Tariq Chaichan, 2015)in their tests, where the CR was augmented to 19 with a 40% hydrogen injection rate. This, however, presents a concern as greater hydrogen input significantly elevates the danger of aberrant combustion at higher compression ratios. Sharma and Dhar demonstrated that optimizing the compression ratio enabled hydrogen injection up to forty-five percent without inducing aberrant combustion. Elevating both the compression ratio and hydrogen substitution rates will enhance thermal efficiency and reduce carbon monoxide and hydrocarbon emissions, albeit with a corresponding rise in nitrogen oxide emissions. Elevated NOx emissions may arise from suboptimal compression ratio and hydrogen substitution balance, necessitating optimization to regulate emission levels, particularly when hydrogen possesses a higher calorific value, potentially resulting in increased combustion temperatures.
- Water injection cools the combustion chamber, reducing exhaust temperatures, mitigating NOx emissions, and knocking in hydrogen-diesel dual-fuel engines. Water can be introduced into the intake manifold or combustion chamber to utilize the heat of vaporization, reducing cylinder temperatures and the length of banging. Water injection has facilitated an increase in the diesel substitution ratio and resulted in cost reductions in fuel use. Water injections raised knock-limited power output by 39% and prolonged ignition delay, reducing the combustion rate, decreasing peak cylinder pressure, and enhancing braking fuel efficiency. Moreover, water injection amplifies combustion noise and diminishes engine vibrations within the combustion chamber. Chintala and Subramanian reported that thermal efficiency increased under higher loads, but NOx emissions were reduced by up to 24% due to water injection.
- Further, hydrogen possesses combustive characteristics, which are used in advanced combustion strategies such as Homogeneous Charge Compression Ignition (HCCI) and Reactive Controlled Compression Ignition (RCCI). Both are promising ways to enhance engine performance and decrease harmful emissions.

- HCCI combustion involves a hydrogen-oxygen-air mixture that is compressed without a spark ignition. Thus, in HCCI mode, combustion is initiated not by a spark plug but by an internal thermal compression of the gases, as in a diesel engine, only this is in a pre-mixed state. The main benefit of HCCI combustion technology over SI engines is higher thermal efficiency because there are no throttling losses, unlike in SI modes of operation.
- Hydrogen-fueled HCCI combustion presents an additional potential, yet challenges emerge about hydrogen combustion due to its rapid burning rate. The self-ignition temperature of hydrogen is approximately 858 K (585 °C), far lower than that of many hydrocarbon fuels, indicating that the fuel may ignite before the completion of the compression stroke. A consistent mixing ratio could always handle this. The control methods involve precisely measuring the bulk flow within the parameters that dictate stretching invariance and precise temperature and pressure.
- RCCI is yet another powerful combustion technique. It is HCCI, but one fuel with low reactiveness is substituted with a fuel with a different but higher energy level of reactivity. Usually, the RCCI engine consists of a low-reactivity fuel, hydrogen, and a more reactive fuel like diesel, which is injected later in the compression stroke for combustion initiation. This method significantly influences the combustion process because non-reactive fuel can be injected at a necessary time, and it helps control when the combustion will occur. The primary aim in realizing successful RCCI operation is controlling ignition delay and combustion phase since both are necessary to prevent knocking and achieve a smooth rise of pressure. Combustion is achieved in RCCI engines, permitting completion of the cleaning of low NOx and particulate emissions with no power decrease.
- One of the particularities one encounters in hydrogen-fueled engines is the management of pre-combustion processes, knocking, and back-firing. Abnormal combustion phenomena, including pre-ignition, knocking, and backfire, are some of the engrossing issues in hydrogen-fueled engines. In such events hydrogen has low ignition energy with a high-speed flame and therefore leads to an uncontrolled combustion results breaking the engine and is inefficient. Pre-ignition usually causes knocking, where the end gas, the un-burned charge in the cylinder, self-fires due to the very high pressures and temperatures within the cylinder. The intensity of knocking can be measured quantitatively by the following relation

$$I_{knock} = \frac{P_{max}}{\text{Octane Number}} \cdot \left(\frac{T_{end\text{-}gas}}{T_{auto}}\right)^{\gamma-1}$$

- Where $P_{max}$ is the peak pressure, $T_{end\text{-}gas}$ is the temperature of the end-gas, and $T_{auto}$ Is the autoignition temperature. Knocking is particularly damaging to engine components because it generates high-frequency pressure oscillations that can lead to mechanical failure. This formula relates the knocking intensity to the octane number, peak pressure me, and temperatures. P max is the peak pressure, T end-gas is the end gas temperature, and $T_{auto}$ is the auto-ignition.
- Several control strategies are employed to prevent knocking and other abnormal combustion events. These include retarding the ignition timing to reduce peak pressures, using exhaust gas recirculation (EGR) to lower combustion temperatures, and injecting water or other fluids into the combustion chamber to absorb heat and lower the in-cylinder temperature. These measures are critical for maintaining engine durability and performance in hydrogen-fuelled engines.
- Ignition timing is a major control strategy for hydrogen combustion. In gasoline, ignition timing is adjusted to coincide with the rotation angle of the cycle. However, hydrogen has a high charge density, making it prone to suicide events like pre-ignition and backfire. To improve power generation and reduce the risk of engine knocking, ignition timing is adjusted relative to combustion chamber temperatures and pressures.
- Exhaust gas recirculation (EGR) is another effective control strategy for hydrogen engines. It reduces the percentage of oxygen in the intake charge, reduces peak combustion temperature, prevents NOx formation, and lowers the likelihood of knocking. EGR rates can be as high as 30% without affecting performance.
- Water injection is a sophisticated control technique used in hydrogen-fueled engines to suppress knocking and increase temperature. It is beneficial for cylinders with high compression ratios, as hydrogen engines have high flame speed and quick combustion. Injecting water in micro-fine droplets can help reduce the peak temperature of the phenomenon, allowing the engine to operate at higher compression ratios and ignition advance angles without risking knocking or excessive formation of NOx.
- Other than Combustion control, hydrogen-based combustion engines face challenges such as combustion instabilities, which can lead to structural failure and lower efficiency. To address these issues, scientists design combustion chambers that improve air-fuel mixing and prevent ignition through hot spots. Other swirling technologies are employed to enhance fuel distribution and stabilize the flame. The durability of materials is also

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 01, January 2025, pp : 1781-1793
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

crucial, as high temperatures can cause significant thermal stresses in engine elements. Additives like nickel-based superalloys and ceramic coatings can improve wear and tear resistance. Hydrogen embrittlement is a factor in some fuel pour systems, making it essential to develop materials with solid resistance to hydrogen embrittlement for engine safety. Developing hydrogen infrastructure and supply chain is crucial for the broader application of hydrogen-fueled engines. Water electrolysis is the most environmentally friendly production method, but current technologies have an efficiency rate of 60-70%.

**Calculations to Elaborate Hydrogen Engines Combustion** (L. Gao, 2023)

The paper runs a Python /Cantera Cobe to present different Criteria that will help in the general understand of hydrogen Engine combustion as a bask case of study.

Hydrogen, a high-speed combustion fuel, has a laminar flame speed of approximately 3.1 m/s, significantly higher than conventional hydrocarbon fuels like Methane and Propane. This is due to its low molecular weight, high diffusivity, and fast reaction kinetics, allowing for rapid energy release and combustion stability. Hydrogen's faster flame propagation enables more efficient and complete combustion, reducing unburned hydrocarbons and increasing thermal efficiency. However, this high reactivity also introduces challenges such as flashback risks in premixed systems, necessitating specialized combustion strategies for safe operation. Methane and Propane, with their slower flame speeds, are well-suited for steady and controlled combustion applications like gas turbines and industrial burners. Hydrogen's high flame speed allows lean-burn operation, reducing nitrogen oxide emissions while maintaining high efficiency. However, its application requires careful design considerations to manage flame stability, quenching distance, and potential detonation risks. The bar chart highlights the significant disparity in flame speeds, reinforcing Hydrogen's role as a high-speed combustion fuel suitable for next-generation low-emission energy systems, hydrogen-powered engines, and aerospace propulsion technologies.

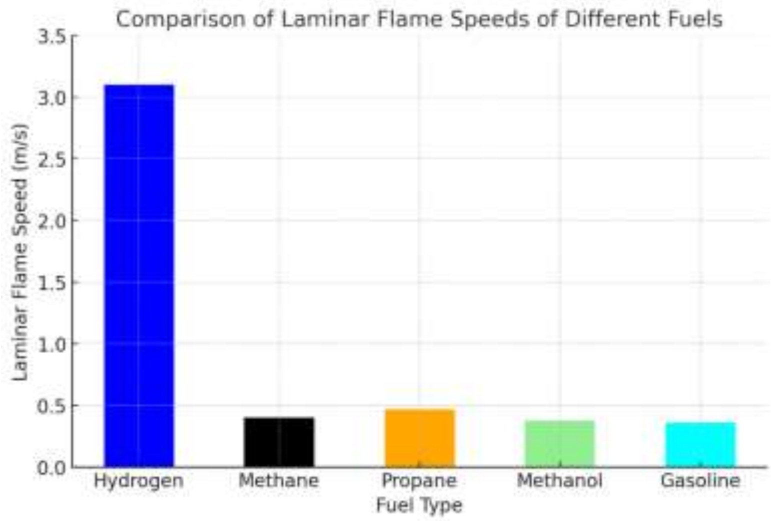


**Fig 1** Flame Speed for different Fuel Types

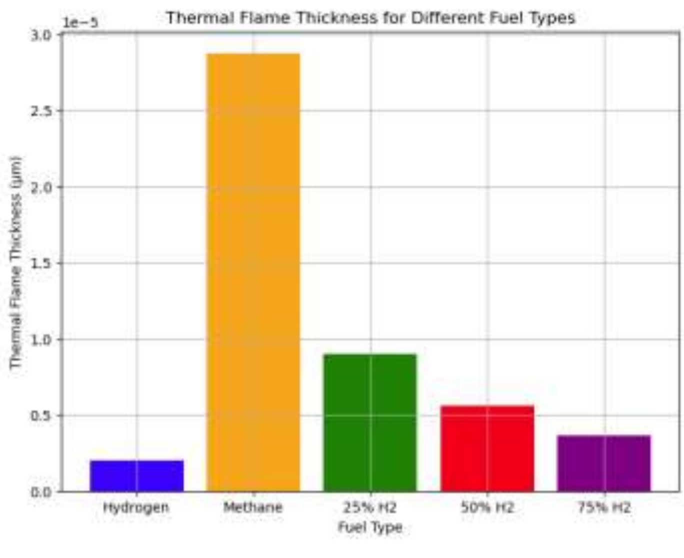


**Fig 2** Flame Thickness for different fuel types

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 01, January 2025, pp : 1781-1793
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

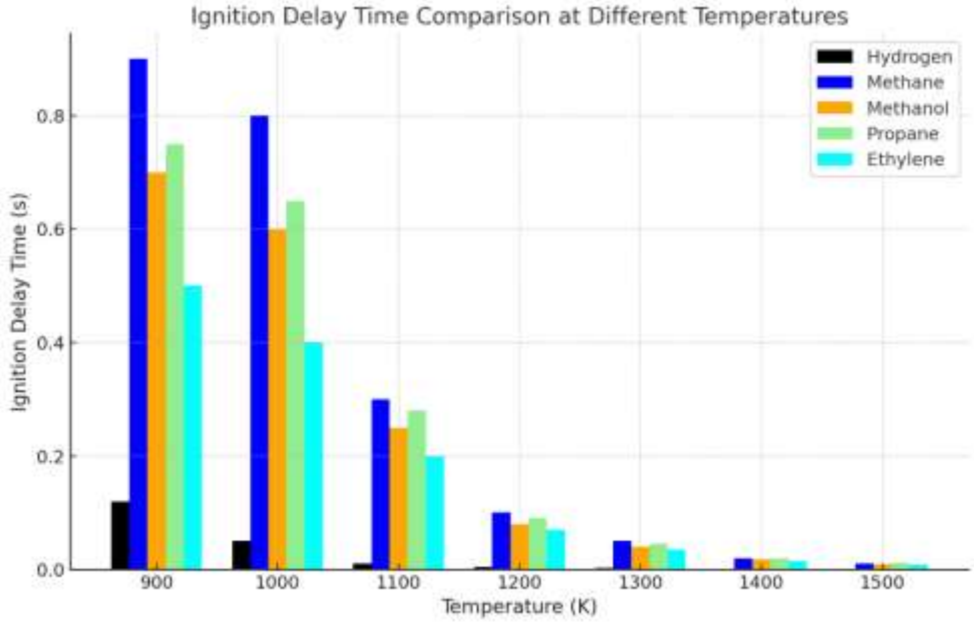


**Fig 3** Ignition Delay for different fuels

This study examines ignition delay times for Hydrogen, Methane, Methanol, Propane, and Ethylene across a temperature range of 900K to 1500K at a constant pressure of 1 atm. The results show that Hydrogen has the shortest ignition delay due to its high reactivity and fast chemical kinetics, making it a promising candidate for high-speed combustion applications. Methane, on the other hand, displays the longest ignition delay across all temperatures, indicating its high chemical stability and slower reaction pathways. Methanol and Propane showed similar trends, with Methanol showing a slightly shorter ignition delay at lower temperatures, highlighting its potential as a cleaner alternative fuel with improved ignition characteristics. Ethylene, a fundamental hydrocarbon in combustion kinetics, exhibited moderate ignition delay behavior, positioning it between Hydrogen and Methane in terms of reactivity.

The influence of temperature on ignition delay was significant, with all fuels showing an exponential decrease in ignition delay as temperature increased beyond 1200K, reflecting enhanced chemical reaction rates at elevated temperatures. The engineering implications of these findings are substantial, particularly in optimizing fuel selection for different combustion applications. Hydrogen and Ethylene are ideal for high-speed combustion processes, while Methane and Propane are more suitable for steady, controlled combustion environments. Methanol, with its intermediate ignition delay and potential for low emissions, is an attractive candidate for future sustainable combustion applications.

These insights contribute to the broader understanding of fuel behavior in advanced combustion technologies, guiding developments in engine design, alternative fuel research, and combustion modeling for improved efficiency and reduced emissions. Future studies can further explore the impact of pressure variations on ignition delay, assess fuel blends, and analyze ignition behavior under high compression ratios relevant to Homogeneous Charge Compression Ignition (HCCI) and Spark Ignition (SI) engines..

## 3. CONCLUSION

Hydrogen offers a highly promising alternative fuel for internal combustion engines, attributed to its distinctive combustion characteristics, elevated energy content, and negligible carbon emissions. In comparison to traditional hydrocarbon fuels, hydrogen demonstrates a markedly elevated laminar flame speed (~3.1 m/s), wider flammability limits (4%–75%), and reduced ignition energy (0.02 mJ), rendering it very reactive and efficient for combustion purposes. The examination of ignition delay times throughout a temperature spectrum of 900K to 1500K underscores hydrogen's swift ignition properties, validating its appropriateness for high-velocity combustion settings. Hydrogen combustion, despite its elevated autoignition temperature (585°C) facilitating enhanced compression ratios and efficiency, presents technical hurdles like flashback, pre-ignition, and NOx generation, necessitating sophisticated fuel injection systems and combustion management techniques. The juxtaposition with methane, propane, and methanol further underscores hydrogen's pre-eminence in facilitating efficient and clean energy conversion, characterized by reduced ignition delays and enhanced flame propagation rates. Nonetheless, proficient regulation of combustion instabilities, turbulent flame dynamics, and thermal NOx emissions is essential for practical application in automotive and power generating systems. Future research should concentrate on hydrogen mixing techniques, the optimization of air-fuel ratios, and alternative combustion methodologies such as HCCI (Homogeneous Charge Compression Ignition) and RCCI (Reactivity Controlled Compression Ignition) to improve thermal efficiency and reduce emissions. The results underscore hydrogen's capability as a high-efficiency, low-emission fuel for advanced internal combustion engines and sustainable energy systems, presenting a feasible route to decarbonization in the transportation and energy sectors.

## 4. REFERENCES

[1] A. Keromnes, W. K.-J. (2013). An experimental and detailed chemical kinetics model for hydrogen-methane mixture oxidation at elevated pressures. Combustion and Flame,, vol. 160, no. 6, pp. 995-1011.

[2] A. Teymoori, A. K. ( 2020). Validation of a Predictive Model of a Premixed Laminar Flame Speed for Hydrogen/Methane-Air Combustion for Internal Combustion Engines. Energy Reports, vol. 6, pp. 1200–1211. doi:10.1016/j.egyr.2019.12.034.

[3] Dhar, P. S. (2018). Compression ratio influence on combustion and emissions characteristic of hydrogen-diesel dual-fuel CI engine: numerical study. Fuel, vol. 222, pp. 852–858. doi:10.1016/j.fuel.2018.02.056

[4] Dimitriou, P. K. (2018). Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine. International Journal of Hydrogen Energy,, 43*(2018), 13605-13617. doi: https://doi.org/10.1016/j.ijhydene.2018.05.062

[5] H. S. Homan, R. K. (1979 ). Hydrogen-fueled diesel engine without timed ignition. International Journal of Hydrogen Energy, vol. 4, pp. 315–325. doi:10.1016/0360-3199(79)90006-5

[6] K. J. Lee, Y. R. (2013). Feasibility of compression ignition for hydrogen-fueled engine with neat hydrogen-air pre-mixture by using high compression. International Journal of Hydrogen Energy,, vol. 38, pp. 255–264. doi:10.1016/j.ijhydene.2012.10.013

[7] Karagöz, T. S. (2014). Experimental investigation of the combustion characteristics, emissions and performance of hydrogen port fuel injection in a diesel engine,. International Journal of Hydrogen Energy, vol. 39, pp. 18480–18489. doi:10.1016/j.ijhydene.2014.09.044

[8] Kiverin, Y. a. (023). Numerical Modeling of Hydrogen Combustion: Approaches and Benchmarks. Fire, vol. 6, no. 2, 2, pp. 239. doi:10.3390/fire6060239

[9] L. Gao, J. L. ( 2023). Hybrid emission and combustion modeling of hydrogen-fueled engines. International Journal of Hydrogen Energy,, vol. 48, no. 15, pp. 1245-1260. doi:10.1016/j.ijhydene.2023.04.033.

[10] Li, C. W. (2023). Numerical Investigation on NOx Emission of a Hydrogen-Fuelled Dual-Cylinder Free-Piston Engine. . Applied Sciences, , 13(3), 1410. doi:https://doi.org/10.3390/app13031410

[11] M. F. Rosati and P. G. Aleiferis. (2009). Hydrogen SI and HCCI combustion in a direct-injection optical engine. SAE International Journal of Engines, vol. 2, pp. 1710–1736. doi:doi: 10.4271/2009-01-1771

[12] M. Huang, Q. L. ( 2024.). Experimental investigations of the hydrogen injectors on the combustion characteristics and performance of a hydrogen internal combustion engine. Sustainability, vol. 16, no. 5, pp. 1940.

[13] M. Ikegami, K. M. (1975). A study on hydrogen-fuelled diesel combustion (1st report). Preprints of the Japan Society of Mechanical Engineers, , vol. 750, pp. 239–242.

[14] M. Ikegami, K. M. (1980.). A study on hydrogen-fuelled diesel combustion. Bulletin of the Japan Society of Mechanical Engineers, ,vol. 23.

[15] M. T. Chaichan and D. S. M. Al-Zubaidi. (2015). A practical study of using hydrogen in dual-fuel compression ignition engine. International Publication Advanced Science Journal (IPASJ, vol. 2, pp. 1–10.

[16] Miqdam Tariq Chaichan, D. S. (2015). A practical study of using hydrogen in dual – fuel compression ignition engine. Researchgate .

[17] Nagarajan, N. S. (2009). Experimental investigation on a DI dual fuel engine with hydrogen injection. International Journal of Energy Research, , vol. 33, pp. 295–308. doi:10.1002/er.1477

[18] Nikitin, N. N. (2014). Modeling and simulation of hydrogen combustion in engines. International Journal of Hydrogen Energ, vol. 39, no. 2, pp. 1122–1136. doi:10.1016/j.ijhydene.2013.10.097

[19] P. Dimitriou, T. T. (2018). Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine. ” International Journal of Hydrogen Energy, , vol. 43, pp. 13605–13617. doi:10.1016/j.ijhydene.2018.05.062

[20] Q.T. Dam, F. H. (2024). Modeling and simulation of an internal combustion engine using hydrogen: A MATLAB implementation approach. Engineering Perspective,, vol. 4, no. 3, pp. 108-118. doi:10.29228/eng.pers.76219

[21] Qing-he Luo, J.-B. H.-g.-s.-z. (2019). Effect of equivalence ratios on the power, combustion stability and NOx controlling strategy for the turbocharged hydrogen engine at low engine speeds. International Journal of Hydrogen Energy, Vol 44 no 44 17095-17102. doi:https://doi.org/10.1016/j.ijhydene.2019.03.245

[22] R.A. Bakar, W. K. (May 2022). Experimental analysis on the performance, combustion/emission characteristics of a DI diesel engine using hydrogen in dual fuel mode. International Journal of Hydrogen Energy,.

[23] S. K. V, R. S. (2014). Experimental Investigation of the Effect of Hydrogen Addition on Combustion Performance and Emissions Characteristics of a Spark Ignition High-Speed Gasoline Engine. In Proc. 2nd Int. Conf. Innov. Autom. Mechatronics Eng. (ICIAME), pp. 1-8.

[24] S. Molina, R. N.-S.-G. (2023). Experimental activities on a hydrogen-fueled spark-ignition engine for light-duty applications,. Applied Sciences, vol. 13, no. 12055, pp. 1-15. doi:10.3390/app132112055.

[25] Stoke, W. H. (1930.). Hydrogen-cum-oil gas as an auxiliary fuel for airship compression ignition engines. British Royal Aircraft Establishment, , Report No. E 3219.

[26] Subramanian, V. C. (2014). "Hydrogen energy share improvement along with NOx (oxides of nitrogen) emission reduction in a hydrogen dual-fuel compression ignition engine using water injection. Energy Conversion and Management,, vol. 83, pp. 249–259. doi:10.1016/j.enconman.2014.03.075

[27] T. Tsujimura and Y. Suzuki. (2017). The utilization of hydrogen in hydrogen/diesel dual-fuel engine. International Journal of Hydrogen Energy, , vol. 42, pp. 24470–24486, . doi:10.1016/j.ijhydene.2017.07.232

[28] Tsujimura, M. D. (2019). "A fully renewable and efficient backup power system with a hydrogen-biodiesel-fueled IC engine. Energy Procedia,, vol. 157, pp. 1305–1319. doi:10.1016/j.egypro.2018.11.210

[29] Tsujimura, Y. S. (2015). "The combustion improvements of hydrogen/diesel dual fuel engine. SAE Technical Paper. doi:10.4271/2015-01-1939.

[30] Verhelst, Y. W. (2023). Comparative analysis and optimization of hydrogen combustion mechanism for laminar burning velocity calculation in combustion engine modelling,. International Journal of Hydrogen Energy, vol. 48, no. 1, pp. 112-125,. doi:10.1016/j.ijhydene.2022.12.214