Use of Hydrogen in Internal Combustion Engines: A Comprehensive Study
Parashuram R Chitragar*, Shivaprasad K V**, Kumar G N***

*Department of Mechanical Engineering, VPKBIET Baramati, India
**Department of Automotive Engineering, College of Engineering and Technology, Dilla University, Ethiopia
***Department of Mechanical Engineering, NITK Surathkal, India

Abstract

Hydrogen’s combustion properties made it as a capable fuel to combat the current situations of depletion of the fossil fuels and to safeguard the environmental pollution problems. Its energy content per unit mass and higher heating value is almost about three times that of current fossil fuels. Hydrogen ignites across a wide range of concentrations, from about 4 to 74 percent, and only requires a small amount of energy to initiate ignition. Moreover when hydrogen reacts with oxygen to generate energy, the resulting reaction product is water vapor.

In view of the above hydrogen can be used as a fuel in internal combustion engines or in fuel cell vehicles. In this paper a thorough review was made to bring awareness among buddy researchers working on hydrogen about combustion fundamentals, its anomalies, fuel induction strategies, performance, emission and safety related aspects for utilizing it in IC Engines as an alternative fuel.

2016 Published by Rational Publication.

Keywords: IC Engine; Hydrogen; Injection; Ignition; Performance; Emissions; Safety

1 Introduction

Petroleum and its derivatives are in phase of depletion. On the other side automotive emissions are increasing due to use of fossil fuels. Meanwhile stringent emission regulations on automotive provoked many of the researchers to search for the feasible alternative fuel for the internal combustion (IC) engines. Among the available alternative fuel options; hydrogen finds prominent place to replace the present fossil fuels in IC engines. Hydrogen is available abundantly in nature and gives near zero-emissions when used in IC engines. It can be used in fuel cells or directly in IC engines [1-3].

The attempt of developing a hydrogen engine was reported by R.W. Cecil in the early of the 19th century itself. During mid of the last century Otto used synthetic producer gas which probably had a hydrogen content of over 50%. Hydrogen has since been used extensively in the space program since it has the best energy-to-weight ratio of any fuel & lighter than other fuel and has been utilized in the upper stages of launch vehicles on many space missions and for rocket engines.
Perhaps hydrogen is the ideal fuel in view of its ability to be produced from a host of non-fossil sources \[^{4-5}\]. Hydrogen combustion does not produce any of the major pollutants such as carbon monoxide (CO), hydrocarbon (HC), sulphur oxides (SO\(_x\)), smoke etc. An oxide of nitrogen (NO\(_x\)) is the single pollutant which needs to be closely monitored\[^{6-7}\]. Thus, hydrogen is probably the unique versatile fuel which provides permanent solutions to fuel dependency, fuel depletion and global environmental problems. This paper tried to provide an overview of hydrogen as a possible major fuel of the future, which can be used in an internal combustion engines.

2. Scope for Hydrogen.

Internal combustion engines are either spark ignition (SI) engines or compression ignition (CI) engines. An IC engine can be run on different fuels. Currently practical SI engines are gasoline operated whereas CI engines use diesel as their major fuel. Hydrogen is one of the energy carriers which can replace fossil fuel and can be used as electricity generator in fuel cell vehicles (FCV) or as a fuel in hydrogen fueled internal combustion engines (\(H_2ICE\)).

Fuel cell vehicles using hydrogen are attractive for their potential efficiency, quiet running, modular and their emission is only water vapor \[^8\]. On the other hand, they require excessively high purity hydrogen, need more space and weight to install the battery and storage tank and hence they are currently compromised due to cost and durability concerns \[^2\].

On the other hand, hydrogen internal combustion engines offer a number of very interesting advantages. They are less expensive and they run with hydrogen of only industrial purity \[^2\]. There are different ways to use hydrogen as a fuel in IC engines; it can be used in liquid state, or in gaseous state. A cryogenic storage up to capacity of 20K approximately is required if it is used in liquid state but is injected in gaseous state or it can be used in gaseous state like liquid petroleum gas (LPG) and compressed natural gas (CNG). Gaseous hydrogen storage systems are large and heavy wherein liquid hydrogen storage systems are much smaller and lighter but must operate at cryogenic temperatures. Hydrogen can also offer the opportunity of running on mixed fuel with gasoline and diesel fuel \[^9,10\].

3. Hydrogen as a Fuel

3.1 Hydrogen Production

Hydrogen is produced from a wide range of primary resources, employing wide range of technologies. Despite its abundance occurrence in the universe, it does not occur freely on earth, as it reacts very rapidly with other elements. For this reason, the majority of hydrogen is bound into molecular compounds. The hydrogen can be extracted from higher energy fossil fuels or lower energy water \[^{13}\].

![Fig. 1](https://example.com/hydrogen_production_path.png)

**Fig. 1** Hydrogen production path\[^{30}\]
Alternative methods of hydrogen production include thermochemical water decomposition, photo conversions, photo biological processes, production from biomass, and industrial processes. A hydrogen production path is summarized in Fig 1.

3.2 Combustive Properties of Hydrogen

Combustion properties of hydrogen are presented in Table 1, and are detailed below:

3.2.1) Flammability: Hydrogen has a wide flammability range of 4-75% in comparison with all other fuels. As a result, hydrogen can be combusted in an IC engine over a wide range of fuel-air mixtures. A significant advantage of this is that hydrogen can run on a lean or rich mixture [7].

3.2.2) Ignition Energy: Ignition energy is the amount of energy required to ignite a combustible vapor or gas mixture. At atmospheric conditions, hydrogen has very low ignition energy. The minimum ignition energy of a hydrogen–air mixture is 0.02mJ which is an order of magnitude lower than that required for gasoline. This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition. But it poses problems of premature ignition and back fire.

3.2.3) Quenching Distance: This parameter measures how hydrogen flames can travel closer to the cylinder wall before they extinguish. As compared to gasoline and other fuels, hydrogen has small quenching distance of 0.64 mm against 2.0 mm of gasoline. Consequently, this increases the tendency for backfire.

3.2.4) Auto ignition Temperature: Hydrogen has relatively high auto ignition temperature of 858 K. This high temperature allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine. This higher compression ratio leads to higher thermal efficiency of the engine. On the other hand, hydrogen is difficult to be ignited in a compression ignition engine; because the temperature needed for ignition is relatively high. [12]

3.2.5) Flame Speed: Hydrogen has high flame speed at stoichiometric ratios of nearly 2.65 m/s which is an order of magnitude higher (faster) than of conventional fuels. This means that hydrogen engines can more closely approach thermodynamically ideal engine cycle.

3.2.6) Diffusivity: Hydrogen possesses remarkably high diffusivity of 0.61 cm²/s. This ability to disperse in air is considerably greater than gasoline and is advantageous for two main reasons. Firstly, it facilitates the formation of a uniform mixture of fuel and air. Secondly, if a hydrogen leak develops, the hydrogen disperses rapidly. Thus, unsafe conditions can either be avoided or minimized and leaking hydrogen is not a pollutant to the environment [7, 12].

3.2.7) Density: Hydrogen has very low density of 0.082 kg/m³. This results in two problems of IC engine. Firstly, a very large volume is necessary to store enough hydrogen to provide sufficient driving range. Secondly, it reduces the power output.

3.2.8) Air-Fuel Ratio: The stoichiometric or chemically correct air-fuel ratio for the complete combustion of hydrogen in air is about 34:1 by mass. This is much higher than the air-fuel ratio (14.7:1) required for gasoline. Since hydrogen is a gaseous fuel at ambient conditions it displaces more of the combustion chamber than a liquid fuel. Consequently less of the combustion chamber can be occupied by air. At stoichiometric conditions, hydrogen displaces about 30% of the combustion chamber, compared to about 1 to 2% for gasoline.

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>H₂</td>
<td>C₈H₁₈</td>
<td>C₁₂H₂₃</td>
</tr>
</tbody>
</table>

Table1. Properties of hydrogen, gasoline and diesel [7, 8, 12]
3.3. Use of Hydrogen in Fuel cell vehicles

A fuel cell is an energy conversion device that can operate using a variety of fuels and oxidants. Hydrogen has long been recognized as the most effective fuel for practical fuel cell use since it has higher electrochemical reactivity than other fuels \[12\]. A hydrogen fuel cell converts the chemical energy of hydrogen fuel into electricity without any intermediate thermal or mechanical processes and this energy is used to power the vehicles.

![Fig.2 Hydrogen fuel cell](image)

In hydrogen fuel cell, the hydrogen and the oxidizer (oxygen/air) themselves comprise of an anode, cathode respectively with an electrolyte in between. The hydrogen fuel cell as shown in Fig.2 is suitable for automotive applications which uses low temperature (less than 100°C) and have solid electrolyte that conducts hydrogen ions. Hydrogen fuel cell systems operate without pollution when run on pure hydrogen, the only by products being pure water and heat. But they are costly, heavy and need more space.
3.4. Use of Hydrogen in IC Engines

3.4.1. Use of Hydrogen in Spark Ignition Engines

Hydrogen is an excellent candidate for use in SI engines as a fuel having some unique and highly desirable properties, such as low ignition energy, fast flame propagation speed and wide operational range. The hydrogen fuel when mixed with air produces a combustible mixture which can be burned in a conventional spark ignition engine at an equivalence ratio below the lean flammability limit of a gasoline/air mixture. The resulting ultra-lean combustion produces low flame temperatures and leads directly to lower heat transfer to the walls, higher engine efficiency and lower exhaust of NO\textsubscript{x} emission [7]. Fig.3 shows the use of liquid and gaseous hydrogen in SI engines.

![Fig.3 Use of hydrogen in SI engine](image)

3.4.2. Use of Hydrogen in Compression Ignition Engines

Hydrogen cannot be used as a sole fuel in a compression ignition engine, since the compression temperature is not enough to initiate the combustion due to its higher self-ignition temperature [13]. Hence hydrogen cannot be used in CI engine without the assistance of a spark plug or glow plug. However it can be used as an additional fuel with diesel in CI engines.

Hydrogen as an additional fuel to accompany diesel fuel in CI engine increases the hydrogen to carbon ratio of the entire fuel and injecting it in small amounts to a diesel engine could decrease heterogeneity of a diesel fuel spray due to the high diffusivity of hydrogen which makes the combustible mixture better premixed with air and hence more uniform combustion. Conventional diesel engines can be converted to operate on hydrogen–diesel dual mode with up to about 38% of full-load energy substitution without any sacrifice on the performance parameters such as power and efficiency [14].

4. Combustion Anomalies

The properties that make hydrogen such a desirable fuel for IC engines also bear responsibility for abnormal combustion events associated with it. In particular, the wide flammability limits, low ignition energy and high flame speeds can result in undesired combustion phenomena generally summarized as combustion anomalies. These anomalies include pre ignition (surface ignition), backfiring, rapid pressure rise and auto ignition [15]. The suppression of abnormal combustion in hydrogen engine has proven to be quite a challenge and measures taken to avoid abnormal combustion have important implications for engine design, mixture formation, and load control.

4.1. Pre-Ignition
Pre-ignition is often encountered with hydrogen engines because of the low ignition energy and wide flammability limits of hydrogen. As a premature ignition causes the mixture to burn mostly during the compression stroke, the temperature in the combustion chamber rises, which causes the hot spot that, leads to the pre-ignition to increase in temperature, resulting in another earlier pre-ignition in the next cycle [16]. This advancement of the pre-ignition continues until it occurs during the suction stroke and causes backfire. Pre-ignition is more pronounced when the hydrogen–air mixtures approach stoichiometric level and at higher engine speed and load due to higher gas and component temperatures.

4.2. Backfire

Backfire is a violent consequence of the pre-ignition phenomena. When pre-ignition occur at a point near the inlet valve when the valve is open, the enflamed charge can travel past the valve and into the inlet manifold, resulting in backfire. This problem is particularly dangerous in pre-mixed fuel inducted engines where there is the possibility that an ignitable fuel-air mixture is present in the inlet manifold [17]. The occurrence of backfiring is generally limited to external mixture formation concepts. Any measures that help avoid pre-ignition also reduce the risk of backfiring.

4.3. Auto-Ignition and Knock

Knocking combustion is a common problem found in hydrogen-fuelled engines. When fuel and oxidizer inside the cylinder reaches extremities of temperature then end gas ignites spontaneously without the aid of spark which is termed as auto-ignition, then follows a rapid release of the remaining energy generating high-amplitude pressure waves, referred as engine knock. The amplitude of the pressure waves can cause engine damage due to increased mechanical and thermal stress. The tendency of an engine to knock depends on the engine design as well as the fuel-air mixture properties [18].

5. Fuel Delivery Systems

The mode of fuel induction system plays a critical role for hydrogen operated IC engine. Different fuel induction mechanisms were evaluated experimentally in [19]. Those systems can be grouped into three main types as stated in most of the literatures [1, 20, 21]. Those are discussed in following section.

1. Fuel Carburetion Method (CMI), 2. Inlet Manifold and Inlet Port Injection; and 3. Direct Cylinder Injection (DI)

5.1. Fuel Carburetion Method (CMI)

This is the oldest and simplest technique where gas carburetor is used for carburation of hydrogen fuel. This is also called as central injection system. This system has advantages of not requiring high supply pressure as for other methods and making it easier to convert a standard gasoline engine to hydrogen or a gasoline-hydrogen engine. The disadvantage of this technique is that the volume occupied by the fuel is about 1.7% of the mixture and hence results in 15-20% power loss.

Thus, this method is not at all suitable for hydrogen engine, because it gives rise to uncontrolled combustion at unscheduled points in the engine cycle. Also the greater amount of hydrogen/air mixture within the intake manifold compounds the effects of pre-ignition which leads to back fire[12, 17, 19]. A schematic diagram illustrating the operation of fuel carburetion method is shown in Fig. 4.
5.2. Inlet Manifold and Inlet Port Injection

The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port by using mechanically or electronically operated injector, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. Electronic injectors are robust in design with a greater control over the injection timing and injection duration with quicker response to operate under high speed conditions.

In port injection, the air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots. Since less gas (hydrogen or air) is in the manifold at all time, pre-ignition is less severe \[22\]. The inlet supply pressure for port injection tends to be higher than for carbureted or central injection systems, but less than for direct injection systems \[12\]. A schematic diagram illustrating the operation of inlet port injection is shown in Fig. 5.

In this system, the inducted volume of air per cycle is kept constant and the power output can be controlled by the amount of fuel injected into the air stream, thus allowing lean operation. The fuel can either be metered by varying the injection pressure of the hydrogen, or by changing the injection duration by controlling the signal pulse to the injector \[16\].

5.3. Direct Injection Systems

This system is more technologically sophisticated and involves forming the fuel-air mixture inside the combustion cylinder after the air intake valve has closed. Here hydrogen is injected directly inside the combustion
chamber with the required pressure near the end of compression stroke. As hydrogen diffuses quickly, the mixing of hydrogen with air takes place instantaneously. For ignition spark plug is used as a source. The problem of drop in power output as was in manifold induction/injection can be completely eliminated by this method\textsuperscript{[7]}. A schematic diagram illustrating the operation of direct injection is shown in Fig.6.

![Fig.6 Direct injection system \textsuperscript{[7]}

Direct injection is the most efficient injection system compared to other methods. The power output of a direct injected hydrogen engine is 20\% more than for a gasoline engine. While direct injection solves the problem of pre-ignition in the intake manifold, but it does not necessarily prevent pre-ignition within the combustion chamber\textsuperscript{[12]}. In addition, due to the reduced mixing time of the air and fuel in a direct injection engine, the air-fuel mixture can be non-homogenous\textsuperscript{[23]}.

6. Ignition System

Due to hydrogen’s low ignition energy limit, igniting hydrogen is easy and gasoline ignition systems can be used. At very lean air fuel ratios (130:1 to 180:1), the flame velocity is reduced considerably and the use of a dual spark plug system is preferred.

Ignition systems that use a waste spark system should not be used for hydrogen engines\textsuperscript{[12]}. These systems energize the spark each time when the piston is at top dead center irrespective of running stroke. Therefore the waste sparks acts as a source of pre-ignition for hydrogen engines. For gasoline engines, waste spark systems work well and are less expensive than other systems.

Spark plugs for a hydrogen engine should have a cold rating and have non-platinum tips to avoid oxidization with air as platinum is catalyst. A cold-rated plug has a shorter insulator nose and dissipates heat from the plug tip to the cylinder head quicker than a hot-rated spark plug and firing end stays cooler than hot rated spark plug. The insulator nose of a cold spark plug also has a smaller surface area. This means the chances of the spark plug tip igniting the air-fuel charge is reduced. Hot rated spark plugs are designed to maintain a certain amount of heat so that carbon deposits do not accumulate. Since hydrogen does not contain carbon, hot-rated spark plugs do not serve a useful function.

7. Performance Parameters

7.1. Thermal Efficiency
The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine and the specific-heat ratio of the fuel as shown by the equation (1).

$$\eta_{th} = 1 - \frac{1}{\left(\frac{v_1}{v_2}\right)^{\gamma-1}}$$  \hspace{1cm} (1)

Where $\eta_{th}$ = Theoretical thermal efficiency,

$$\left(\frac{v_1}{v_2}\right)$$ = the compression ratio,

$\gamma$ = Ratio of specific heats.

The thermal efficiency of the engine is higher if the compression ratio and/or the specific heat ratio is higher. The compression ratio limit of an engine is based on the fuel’s resistance to knock. A lean hydrogen mixture is less susceptible to knock than conventional gasoline due to its higher octane number and therefore can tolerate higher compression ratios. The specific-heat ratio is related to the fuel’s molecular structure. Higher the specific-heat ratio lesser the molecular structure complexity. Hydrogen has a much simpler molecular structure than gasoline and therefore its specific-heat ratio ($\gamma = 1.4$) is higher than that of conventional gasoline ($\gamma = 1.1$).

### 7.2. Power Output

The theoretical maximum power output from a hydrogen engine depends on the air-fuel ratio and fuel injection method used.

As mentioned earlier the stoichiometric air-fuel ratio for hydrogen by mass is 34:1. At this air-fuel ratio, hydrogen will displace 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of this mixture will be less than it would be if the fuel were gasoline (since gasoline is a liquid, it only occupies a very small volume of the combustion chamber, and thus allows more air to enter).

Since both the carbureted and port injection methods mix the fuel and air prior to entering the combustion chamber, these systems limit the maximum theoretical power obtainable to approximately 80-85% that of gasoline engines. For direct injection systems, which mix the fuel with the air after the intake valve has closed (and thus the combustion chamber has 100% air), the maximum output of the engine can be approximately 15-20% higher than that for gasoline engines.

Therefore, depending on how the fuel is metered, the maximum output for a hydrogen engine can be either 15-20% higher or 15-20% lesser than that of gasoline if a stoichiometric air-fuel ratio is used. However, at a stoichiometric air-fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides, which is a major pollutant. Since one of the reasons for using hydrogen is low exhaust emissions, hydrogen engines are not normally designed to run at a stoichiometric air-fuel ratio.

Typically hydrogen engines are designed to use about twice as much air as theoretically required for complete combustion. At this air-fuel ratio, the formation of NOx is reduced to near zero. Unfortunately, this also reduces the power output to about half that of a similarly sized gasoline engine. To make up for the power loss, hydrogen engines are usually larger than gasoline engines, and/or are equipped with turbochargers or superchargers.

### 8. Emissions

The combustion of hydrogen with oxygen produces water as its only product:

$$2H_2 + O_2 = 2H_2O$$  \hspace{1cm} (2)

The combustion of hydrogen with air however can also produce oxides of nitrogen (NOx):
The oxides of nitrogen are created due to the high temperatures generated within the combustion chamber during combustion. This high temperature causes some of the nitrogen in the air to combine with the oxygen in the air. The amount of NO\(_x\) formed depends on the air-fuel ratio, compression ratio, engine speed, ignition timing and whether thermal dilution is utilized or not\(^{[12, 24]}\).

In addition to oxides of nitrogen, traces of carbon monoxide and carbon dioxide can be present in the exhaust gas, due to seeped oil burning in the combustion chamber. Depending on the condition of the engine (burning of oil) and the operating strategy used (a rich versus lean air-fuel ratio), a hydrogen engine can produce from almost zero emissions (as low as a few ppm) to high NO\(_x\) and significant carbon monoxide emissions.

Fig. 7 illustrates a typically NO\(_x\) curve relative to equivalence ratio for a hydrogen engine. A similar graph including other emissions is shown in Fig. 8 for gasoline.
As Fig. 8 shows, the NO\textsubscript{x} for a gasoline engine is reduced as equivalence ratio decreases (similar to a hydrogen engine). However, in a gasoline engine the reduction in NO\textsubscript{x} is compromised by an increase in carbon monoxide and hydrocarbons \cite{8, 25}.

### 9. Safety

Taking into account of hydrogen’s lower buoyancy, high auto-ignition temperature, high specific heat and diffusivity, it has been argued that hydrogen is a much safer fuel \cite{26, 27}. Experiments carried out on hydrogen leak in moving vehicle as shown in fig.9 shows that, because of dispersion, the risk of explosion is minimal \cite{28}. It has also been demonstrated that a hydrogen fire causes less damage to a vehicle than a conventional fuel \cite{29}. Some have even argued that in the case of a crash, hydrogen fuel is no more dangerous than conventional fuels. On the other hand, because of its wide range of flammability in air and its low ignition energy, hydrogen as fuel sets new challenges for safety in storage and in use.
10. Conclusions

The key outcomes of this study are summarized below:

- Hydrogen can be used in internal combustion engines either as a fuel, or in terms of a fuel cell.
- Hydrogen can be used in internal combustion engines either as pure or blended with gasoline engine.
- Hydrogen can be used in spark ignition engines with or without any modifications in the existing systems.
- Pre-ignition can be avoided by adopting proper design of injection method and providing cold rated non-platinum type spark plug.
- Backfiring in hydrogen engines is limited to external mixture formation operation and can be avoided by adopting appropriately designed direct injection system.
- Thermal efficiency of the hydrogen operated engine is higher than gasoline and diesel operated engines.
- Power output of hydrogen internal combustion engine is 15-20% more or less than the gasoline or diesel engine which depends upon the fuel injection method adopted.
- H₂ICE are attractive for reducing global warming and local pollutions problems in comparison with gasoline and diesel engines.
- Hydrogen is a safer fuel than conventional fuels.
- Hydrogen engine may achieve lean-combustion in its actual cycles thus reducing NOₓ emissions.

References:


