Analysis on using Hydrogen Gas as a Fuel in Internal Combustion Engines with the Production of Hydrogen through Electrolysis

Manan Gupta

Department of Aerospace Engineering, VIT Bhopal University, Sehore, M.P, India
176, Somani Nagar, Airport Road, Indore, Madhya Pradesh, India, 452005
Email: *manan.gupta2021[at]vitbhopal.ac.in*
OCRID: 0009-0002-2331-9500

Abstract: ***Commonly used motorcar fuels such as Petrol and Diesel contribute to a large amount of CO_2 emission, directly linking it to global concern of climate change. Finding an alternative fuel or technology which can help reduce the Carbon-di-oxide emission has therefore become a necessity to ensure sustainability of natural resources and fossil fuels for further future use. Before Hydrogen fuel came into existence, the EV's were a better alternative to reduce green-house gas emissions. Nonetheless EV's would seem straightforward from the front but they do come with a lot of, usually ignored, drawbacks involving Lithium-ion Battery usage, which itself produces a lot of carbon while its mining and extraction process, and can produce an amount of carbon as much as or more than the conventional gasoline and diesel vehicles do in combined. Electric Vehicles have a lot of benefits in terms of not using fossil fuel, but the fact that they do have many imperfections, all of which cannot be completely disregarded, makes them a not-so-good-choice.***

Keywords: Hydrogen Fuel, Sustainable System, Internal Combustion

1. Introduction

The concept of mitigating carbon emissions and advancing sustainability entails a captivating solution: the utilization of the volatile element known as "Hydrogen." When Hydrogen is combusted alongside oxygen, it yields water or vapor as a byproduct. Consequently, employing Hydrogen as a substitute for conventional fossil fuels such as petrol and diesel can effectively address the issue of emissions to a degree where it ceases to be a global concern, as water vapor, being a derivative of water, possesses potential for reutilization. This manuscript elucidates the notion of an internal combustion cycle utilizing Hydrogen, depicted through a flow chart. Furthermore, it explores the drawbacks associated with this approach, proposes viable remedies, and addresses the additional requisites and vulnerabilities associated with utilizing a substance as delicate as Hydrogen.

The Automotive Industry stands as a testament to its time-honoured existence, emerging as one of the oldest and most enduring sectors globally, characterized by profound technological advancements that have reshaped the very fabric of human existence and lifestyle. Moreover, it has evolved into a symbol of prestige and distinction among select cohorts. While this industry has undeniably facilitated convenience and efficiency, it has simultaneously engendered a cluster of predicaments whose latent gravity may not be readily apparent, yet possesses the potential to intensify with time. Foremost among these challenges is the pressing issue of pollution, an unfortunate byproduct arising from the combustion of fossil fuels, harnessed as the predominant energy source within the automotive realm. This combustion engenders the emission of carbon, instigating an array of hazards, not only for our delicate environment but also for the physical and mental well-being of both humans and the diverse fauna that co-exist within the natural ecosystem.

In response to the pressing challenge of carbon emissions, the imperative for an alternative fuel source has emerged, paving the way for the exploration of Hydrogen as a formidable contender to supplant conventional fossil fuels. Hydrogen has garnered considerable acclaim as a favoured alternative due to its remarkable attributes, including its remarkably low ignition energy, expansive inflammability limit, and prodigious combustion kinetics [1]. Moreover, the combustion of Hydrogen in the presence of oxygen culminates in the liberation of water or vapor, rendering it an environmentally benign residue of unparalleled consequence. Modern studies and innovative efforts suggest using liquid Hydrogen in fuel cells. But this idea brings up many challenges like how to store it safely and produce it efficiently. Another option is to use Hydrogen gas directly, made by splitting water. This seems appealing because it's clean and sustainable. However, using Hydrogen gas directly also has its pros and cons. It can make the engine hotter and may damage important engine parts like the piston head, fuel injector, and spark plug.

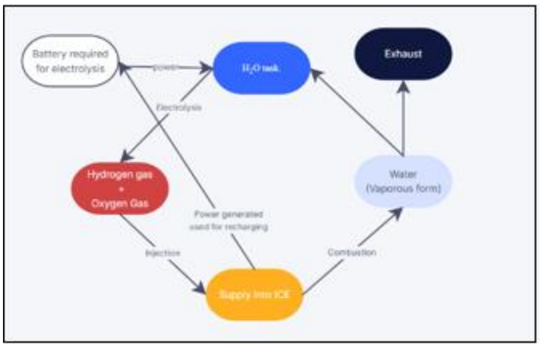
Further, the flow chart will explain the process and cycle of production and combustion of Hydrogen. The drawbacks and challenges will also be discussed in brief, with the possible solutions to the obstacles.

2. Overview of The General Idea

Use of Hydrogen into ICEs can be dated back to the early 1920s and since then it has been a part of a continuous and rigorous research to be used as alternative, clean and green fuel. Full scale use of it has not yet been optimized but it does possess a lot of potential.

The concept arises from the inherent process of water electrolysis, yielding gaseous Hydrogen and Oxygen. These gaseous elements can be harnessed within internal combustion engines (ICEs) to generate motive force for automobiles. The Hydrogen derived from electrolysis shall be directly introduced into the combustion chambers of motor vehicle engines, wherein it shall undergo combustion in conjunction with the produced Oxygen. Consequently, this process shall yield water vapor as a residue, devoid of carbonaceous components, thus representing a pristine and environmentally-friendly fuel source.

2.1 Flow Chart of the Combustion Cycle.



The amount of Hydrogen that injected into the chamber is required to be significantly lower than the petrol and diesel injection, as Hydrogen is highly flammable, and vulnerable substance which produces very high amount of energy. This fuel injection will be regulated by the "Engine Control Module" of the vehicle, so as to ensure proper and accurate amount of fuel is being supplied. The electrolysis will be started by an electric battery which would recharge once the engine starts working, in a cyclic process, as per the mechanism of a car battery in usual vehicles. This would ensure energy savings and also sustainability in future automobiles. Optimization of this idea may require certain different and extra components inside of an automobile.

3. Drawbacks and Challenges

Hydrogen as a clean and green fuel is highly efficient to be used in automobile industry, but as discussed above, it will have its own challenges which can cause sufficient damage to the engine as well as the automobile, if something goes wrong. Therefore, the need of researching about the obstacles is very important.

Damage to piston and valve:
The introduction of Hydrogen injection into the piston valve presents an initial challenge concerning potential damage to the piston head. Structural harm within the engine not only impacts its immediate functionality but also poses risks to its long-term durability. Prior research endeavours have already shed light on the notable impact of thermal fatigue on the exhaust port area adjoining the piston head [4]. Additionally, the choice of materials employed in the engine's design is likely to influence the temperature distribution within the system [4].

The subsequent challenge pertains to all facets associated with the quantity of Hydrogen being injected into the valve. Factors such as high auto-ignition temperature, extensive displacement of the combustion chamber, and low density cannot be disregarded, as they play crucial roles in the overall analysis. A comprehensive understanding of these aspects is indispensable for further advancement and optimization of Hydrogen injection technologies.

High Auto-ignition:
Hydrogen's relatively high autoignition temperature has important consequences when compressing a hydrogen-air mixture. In fact, the autoignition temperature is an important factor in determining what compression ratio an engine can use, since the temperature rise during compression is related to the compression ratio [5]. On the other hand, hydrogen is difficult to ignite in a compression ignition or diesel configuration, because the temperatures needed for those types of ignitions are relatively high [5].

Because hydrogen is a gaseous fuel at ambient conditions, it occupies more space in the combustion chamber compared to a liquid fuel. As a result, there is less room available for air in the chamber. At stoichiometric conditions, hydrogen displaces about 30% of the combustion chamber, compared to about 1 to 2% for gasoline [5].

Combustion Anomalies:
The properties that make Hydrogen such compatible fuel also bear responsibility for irregular combustion associated with Hydrogen fuel. In particular, the wide flammability limits, low required ignition energy and high flame speeds can result in undesired combustion phenomena generally referred as combustion anomalies. These anomalies include surface ignition and backfiring as well as autoignition [6].

Auto-Start temperature:
The temperature needed for the ignition to start in case of Hydrogen is relatively high. Therefore, it becomes a little difficult to lit Hydrogen inside the piston valves of the ICE's. It does provide higher thermal efficiency but Hydrogen when contrasted with different fuels has a large auto start temperature of 858 K [7].

Low-Density:
Hydrogen possessing a very low density of 0.082kg/m3, creates a concern for its storage. Low density means that the air-fuel mixture which will be produced will have a low energy density, due to which it reduces the power output of the engine. Also, a huge volume is required for storing enough H2 to give sufficient range of driving [7].

Also, Hydrogen has a tiny extinguishing separation of 0.6mm for hydrogen. This makes it a real challenge to extinguish hydrogen fire than normal ones, increasing the possibilities of backfire [7].

3.2 Why Hydrogen over other convectional fuels?

One of the many advantages of using Hydrogen is zero-carbon content. This implies that carbon-based emissions such as CO_2, CO can be eliminated. Hydrogen possesses unique qualities as compared to diesel, gasoline and CNG.

Research shows that Hydrogen can provide nearly three times as much energy as compared with other fossil fuels. Also, unlike electricity, hydrogen can be stored and transported over long distances at lower cost [17].

Hydrogen gas is a remarkably light fuel that requires on volume basis the least amount of air for stoichiometric combustion (2.39 versus 59.6 for iso-octane); while on mass basis it requires the highest relative mass of air [13].

Property	Hydrogen	CNG	Gasoline	Diesel
Carbon content (mass%)	**0**	75 [e]	84	86
Lower heating value (MJ/kg)	**119.7**	45.8	44.8	42.5
Density [a,b] (kg/m^3)	**0.089**	0.72	730–780	830
Volumetric energy content [a,b] (MJ/m^3)	**10.7**	33.0	33×10^3	35×10^3
Molecular weight	2.016	16.043 [e]	~110	~170
Boiling point [a] (K)	20	111 [e]	298–488	453–633
Auto-ignition temperature (K)	**858**	813 [e]	~623	~523
Minimum ignition energy in air [a,d] (mJ)	**0.02**	0.29	0.24	0.24
Stoichiometric air/fuel mass ratio	34.5	17.2 [e]	14.7	14.5
Stoichiometric volume fraction in air (%)	29.53	9.48	~2 [f]	-
Quenching distance [a,c,d] (mm)	**0.64**	2.1 [e]	~2	-
Laminar flame speed in air [a,c,d] (m/s)	**1.85**	0.38	0.37–0.43	0.37–0.43 [g]
Diffusion coefficient in air [a,b] (m^2/s)	8.5×10^{-6}	1.9×10^{-6}	-	-
Flammability limits in air (vol%)	4–76	5.3–15	1–7.6	0.6–5.5
Adiabatic flame temperature [a,c,d] (K)	2480	2214	2580	~2300

[a] at 1 bar, [b] at 273 K, [c] at 298 K, [d] at stoichiometry, [e] methane, [f] vapor and [g] n-heptane.

Large Flammability Range:
Researches show that huge combustibility rate of Hydrogen is between 4-7.5 % compared to other fuels, which rises concerns about its management. But also on the other hand, it has large range of F-A mixtures, along with a lean mixture of F/A. These, in turn felicitate clean-green combustion of fuel [7].

High diffusivity:
Hydrogen has a diffusion coefficient of 0.61 cm. This implies that it has the potential to scatter in air much more than the gasoline. Further, this favours the development of uniform fuel-air mixture. Also, in case of a leak, there would be a rapid dispersion of hydrogen, and it will not contaminate the environment [7]

High flame propagation rates:
Hydrogen exhibits rapid flame propagation rates inside the engine cylinder, maintaining significant speed even for lean mixtures distant from the stoichiometric range.
This characteristic results in swift energy release and short combustion duration, ultimately leading to the generation of high-power output subsequent to spark ignitions [13].

Low boiling Temperature:
Hydrogen having low boiling temperature leads to fewer problems which are mostly encountered in cold weather operations. Also, the fast-burning property of Hydrogen allows much more significant high-speed operation [19].

High Autoignition Temperature:
Hydrogen having a high autoignition temperature has important applications when a hydrogen air mixture is compressed. Even, blending it in petrol engine can improve the burning rate of mixture and reduce misfire. It burns more sufficiently thus; more energy can be obtained [20]. This property of hydrogen allows larger compression ratios which might be used in a hydrogen engine rather than a hydrocarbon engine [5].

3.2 Some more features of Hydrogen for Engine Application

Aside from the above-mentioned special characteristics associated almost solely with hydrogen, a number of additional might be offered in support of hydrogen usage in engines. The following are some of the most important of these features:

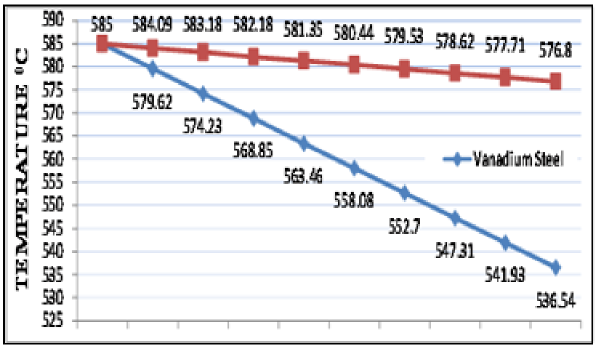
- With a mere energy threshold of 0.02 mJ, the ignition of a hydrogen-air mixture can be achieved. This minimal requirement empowers hydrogen engines to efficiently operate on lean fuel mixtures, guaranteeing swift and reliable ignition [19].
- In contrast to other fuels, the operation of a hydrogen engine results in fewer undesirable exhaust emissions. Notably, there are no emissions of unburned carbon monoxide (CO) or carbon dioxide (CO2) gases [20].
- Diverging from the majority of fuels, hydrogen possesses the unique ability to be utilized as a pure fuel. This characteristic enables sustainable and superior optimization of engine performance [13,20].
- Exclusively, hydrogen stands as the sole fuel that can be entirely derived from the abundant renewable resource of water, despite the substantial energy investment required for its production. Conversely, when hydrogen undergoes combustion with oxygen (O2), it exclusively yields water as the sole byproduct.
- The production of hydrogen with a level of purity suitable for fuel cell applications can be achieved through water electrolysis, with thermal efficiency ranging from 60% to 75% [22].
- The rapid ignition characteristic of hydrogen contributes to the robustness of a hydrogen-powered engine's performance, making it less sensitive to variations in factors such as the combustion chamber design, turbulence level, and the vertical influence of the induction charge [23].
- Hydrogen has a small molecular size, allowing it to permeate through certain materials more easily than other

gases. This property poses challenges for containment and requires specialized materials and safety measures to prevent leaks.

- Utilizing hydrogen as a gaseous fuel instead of a liquid one eliminates various challenges, including soot formation, difficulties in achieving fuel atomization and evaporation during cold start and warm-up phases, uneven fuel distribution among cylinders caused by liquid film formation on intake manifold walls, and undesired fluctuations in air-fuel ratio during transient conditions like acceleration and deceleration [23].
- Hydrogen-powered engines are particularly well-suited for operating high-speed engines primarily due to the associated rapid combustion rates.
- In contrast to the majority of conventional fuels, hydrogen stands as a pure fuel with well-known properties that enable continuous and enhanced optimization of engine performance. The reaction rate of hydrogen (H2) is sensitive to the presence of various catalysts, which enhances combustion and exhaust gas management. Additionally, the thermodynamic and heat transfer properties of hydrogen contribute to its favourable characteristics [7].
- The presence of a diverse range of catalysts significantly influences the reaction rates of hydrogen. This sensitivity plays a crucial role in enhancing hydrogen's combustion process and facilitating effective exhaust emissions treatment. Furthermore, the thermodynamic and heat transfer properties of hydrogen result in elevated compression temperatures, which contribute to improved engine efficiency and enable lean mixture operation.

3.3 A note on potential solutions to the drawbacks discussed:

1) In their research article titled "Design and Analysis of Piston in Hydrogen-Fuelled Internal Combustion Engine" [15], Mani.R, Karthikeyan.V.S. P propose a potential solution to address the problem at hand. By substituting the conventional aluminium-silicon alloy with vanadium steel as the material for manufacturing piston heads, they demonstrate the ability to mitigate piston and valve damage concerns. The following graph in their paper demonstrates the temperature variation which shows that vanadium steel has less temperature distribution when compared to aluminium silicon alloy, which makes its much more suitable for intended use.



2) The propensity of hydrogen to exhibit high autoignition can be effectively ameliorated through a multitude of strategies. Among these approaches is the fine-tuning of the engine's operational parameters, encompassing the manipulation of the compression ratio and spark timing, to optimize the ignition sequence and circumvent untimely combustion events.

   Furthermore, the integration of advanced ignition systems, such as laser ignition or multi-point spark ignition, confers meticulous control over ignition timing, fostering enhanced combustion efficiency. Moreover, the introduction of appropriate additives or diluents into the hydrogen fuel blend can elevate its ignition delay, thereby engendering improved regulation of the combustion process and a reduction in the likelihood of spontaneous autoignition occurrences.

3) Renowned researchers, namely Ricardo and Burstall [24], conducted pioneering investigations that demonstrated the successful utilization of hydrogen as an engine fuel. However, they observed that hydrogen exhibited a propensity for pre-ignition and backfiring into the carburettor. To mitigate pre-ignition, they recommended maintaining a low compression ratio, typically below 5 or 6. Subsequently, Erren embarked on an intensive and dynamic research program focused on hydrogen engines, commencing in Germany and later continuing in England. Erren's contributions were documented extensively through patents and encompassed various critical aspects. Notably, he explored the potential of fuel injection as a viable solution to address the challenges of pre-ignition and backfiring, emphasizing its efficacy in overcoming these issues [24].

4) R. R. ADT, D. L. HERSCHBERGER, T. KARTAGE & M. R. SWAIN in their research paper published in 1973 “The hydrogen-air fuelled automobile Engine” avoided the backfire problem by introducing the hydrogen through a hole in the seat of the intake valve. This is a notable way to prevent backfire problem and can be looked into as a likely solution. They note that the performance of their vehicle is not noticeably different from that of a similar gasoline fuelled vehicle [25]. Also, the entire problem does not arise if the hydrogen is injected directly into the cylinder (direct fuel injection), rather than carburetted but the cost of injection equipment is significantly higher than cost of a carburettor. In most gasoline engines, therefore, the fuel is introduced with carburettors rather than with injectors. The high cost here is at least partially offset by economic operation, and is not a major consideration for large engines [23].

5) It is largely demonstrated by many researchers that the challenge of low density can be eliminated by employing direct injection systems that carefully control the mixture formation and distribution of hydrogen within the combustion chamber. By precisely injecting hydrogen in a controlled manner, it becomes possible to enhance the mixing process and promote more uniform combustion.

Additionally, optimizing the engine design to account for the lower density of hydrogen can help improve its overall performance. This may involve adjusting factors such as the compression ratio, intake and exhaust system design, and

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combustion chamber geometry to accommodate the specific characteristics of hydrogen.

Furthermore, advanced boosting technologies such as turbocharging or supercharging can be utilized to increase the air intake pressure and density, compensating for the lower hydrogen density. These technologies ensure a higher air-fuel mixture density, enhancing combustion efficiency and power output.

3.4 Production of Hydrogen and its use into the ICE's:

Among the myriad approaches to procure hydrogen, the method that emerges as particularly advantageous is the utilization of electrolysis for its production. This process yields hydrogen gas that can be seamlessly introduced into the piston valves, thus optimizing its application. Furthermore, with meticulous research endeavours, the concurrent byproduct, oxygen, can be directly supplied to the valve, thus facilitating the efficient combustion of hydrogen.

In theory, this represents the most straightforward method of hydrogen generation. However, this innovation faces a hurdle in terms of power conversion, as its impurities must be effectively addressed in order to ensure an optimal energy framework, namely electricity. In the current liquid electrolysis process, electrode plating is employed, leading to a reduction in costs associated with the overall procedure. A prospective resolution to surmount this formidable challenge entails replenishing the battery employed for water electrolysis by harnessing the power derived from the engine's own machinations.

Technically, the production of hydrogen extends beyond the confines of electrolysis and encompasses additional methods such as radiolysis, photo catalytic water splitting, and various other approaches. Given its innate reactivity, hydrogen is seldom encountered in its pure gaseous state in natural occurrences. Consequently, the advancement of technology becomes imperative to enable the cost-effective production of hydrogen in a pristine form, thereby unlocking its full potential as an efficient energy carrier.

The engine generates electrical power to run the vehicle and other systems. During the operation of the engine, there is often excess power available that is not fully utilized. The excess power generated by the engine is diverted to recharge the battery used for water electrolysis. This charging process ensures that the battery maintains a sufficient level of charge, allowing it to supply electricity for electrolysis even when the engine is not generating enough power. The battery supplies electricity to the electrolyser, which splits water into hydrogen and oxygen through the process of electrolysis. This generated hydrogen can be stored and used as a clean energy source, a fuel for combustion engines.

By recharging the battery with excess power from the engine, this solution optimizes the use of available resources and ensures a continuous supply of electricity for water electrolysis. It enhances the overall efficiency and sustainability of the system by utilizing excess energy that would otherwise go unused. Moreover, delving deeper into the realms of advanced inquiry, the exploration of hydrogen production via this mechanism, coupled with its direct introduction into the combustion chamber as a gaseous entity, proffers an alternative paradigm that transcends the conventional employment of fuel cells, fraught as they are with their inherent intricacies and entanglements. Top of Form.

3.5 Why not fuel cells?

Hydrogen fuel cells are seen as a highly promising solution in the realm of sustainable energy, holding the potential to revolutionize how we power our world. However, their path to widespread adoption is not without significant hurdles, spanning several critical areas. One of the most pressing challenges lies in the production of hydrogen itself. While hydrogen can be generated through various methods, such as water electrolysis or by transforming fossil fuels, the primary concern is to find clean and environmentally friendly ways to do so. This is crucial for ensuring that hydrogen fuel cells live up to their potential as a sustainable energy source. The current methods of hydrogen production often involve carbon emissions or are energy-intensive, and finding a cleaner and more efficient approach is an ongoing quest. Furthermore, to make hydrogen fuel cells a practical energy source, we need a well-structured and efficient supply chain. This supply chain encompasses the entire journey of hydrogen, from its production to storage, transportation, and distribution. Building such a seamless and dependable system requires substantial investments in cutting-edge infrastructure, which can be a significant barrier to their widespread adoption [26]. In essence, the promise of hydrogen fuel cells as a sustainable energy solution is tempered by the need to address challenges related to clean hydrogen production and the development of a comprehensive and efficient supply chain. Overcoming these obstacles will be essential to fully unlock the potential of hydrogen fuel cells and integrate them into our sustainable energy landscape.

Moreover, hydrogen fuel cells face durability and performance challenges, particularly related to catalyst degradation. Continuous improvements are needed to enhance their longevity and efficiency. Additionally, membrane efficiency and electrode durability require constant attention to improve performance. Material costs also significantly affect the commercial viability of fuel cell construction, necessitating careful consideration in this pioneering field of sustainable energy endeavours

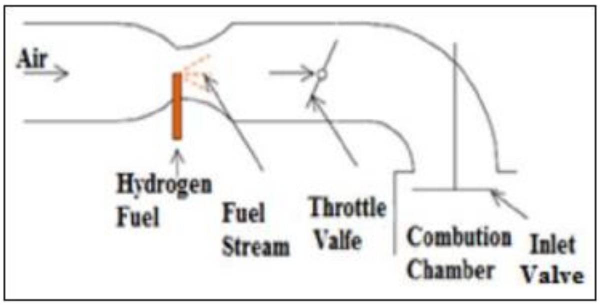
3.6 Fuel Injection Systems & Techniques:

Central Injection or Carburetted Systems:

Within the realm of fuel injection techniques for hydrogen engines, the paradigms of central injection and the venerable carburetted system emerge as the epitome of simplicity and elegance. These systems, adorned with a multitude of virtues, bestow upon the hydrogen-powered engines a plethora of advantages. Foremost among these merits lies the captivating allure of central injection, which defies the need for excessively elevated hydrogen supply pressures compared to alternative methodologies. Within the vast domain of global internal combustion engines, the utilization of central infusion brings forth a trifling fuel volume, accounting for a mere 1.7% of the overall blend [7].

However, when the hydrogen-fuelled engine embraces the carburetted approach, employing gaseous hydrogen, a notable power output reduction of 15% becomes apparent. Consequently, carburetion unveils itself as an unsuitable choice for hydrogen engines, entailing uncontrolled ignition events at unforeseen junctures during the engine cycle. Moreover, the heightened presence of hydrogen/air mixture within the intake manifold intensifies the implications of pre-ignition phenomena. The potential for pre-ignition to manifest while the inlet valve remains ajar in a premixed engine poses the peril of flame propagation beyond the valve, inadvertently igniting or backfiring the fuel-air amalgamation within the intake manifold. In a carburetted hydrogen engine, a substantial segment of the intake manifold harbours a flammable air-fuel blend, mandating utmost cautionary measures to pre-empt any ignition incidents. In the unfortunate occurrence of a backfire, the engine components lay vulnerable to the risk of enduring severe damage [27].

Fuel Carburetion Method [27]:

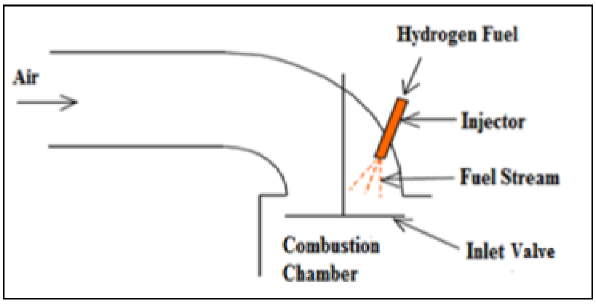


a) Port Injection Systems:

The port injection fuel delivery system represents a cutting-edge technology in the realm of internal combustion engines, wherein fuel is introduced directly into the intake manifold at individual intake ports through either mechanically or electronically operated injectors. This approach deviates from conventional methods that entail a central fuel intake point. Notably, the hydrogen injection process within this system occurs subsequent to the initiation of the intake stroke, further optimizing the combustion process. Electronic injectors, a pivotal component of this advanced system, exhibit remarkable design robustness, affording precise control over injection timing and duration. Their noteworthy responsiveness is particularly advantageous in high-speed operational contexts, where rapid adjustments to injection parameters are vital. Of particular interest in the context of port injection is the independent injection of air at the onset of the intake stroke. This strategic practice serves a twofold purpose: first, by diluting the hot residual gases, it mitigates undesirable combustion events, and second, it effectively cools potential hot spots, fostering an environment conducive to enhanced hydrogen combustion efficiency [27].

In summary, the port injection fuel delivery system, with its sophisticated use of electronically controlled injectors and simultaneous air injection, represents an innovative avenue for optimizing hydrogen-powered internal combustion engines. As the automotive industry seeks environmentally sustainable propulsion solutions, such advancements hold great promise for achieving increased engine efficiency and reduced emissions. Nevertheless, further research and refinement are imperative to fully exploit the potential of this groundbreaking technology.

Port Injection [27]:



b) Direct Injection Method:

An auspicious strategy for enhancing hydrogen engine performance involves direct hydrogen injection into the cylinder during the compression stroke [29]. This approach circumvents the backfiring challenges encountered in port fuel injection (PFI) configurations, as hydrogen injection occurs when the intake valves are fully closed. Moreover, it mitigates pre-ignition issues by reducing the hydrogen mixture's exposure time to hot spots.

The volumetric efficiency loss experienced in PFI, resulting from air displacement by hydrogen, becomes inconsequential when injection takes place after the inlet valves' closure. Injecting fuel late during the compression stroke demands higher injection pressure ($\geq$100 bar) to overcome the augmented in-cylinder pressure. This elevated injection pressure significantly increases the fuel mass flow rate compared to typical low-pressure PFI, consequently providing greater energy input for the same injection duration and facilitating high-load operations. Notably, several studies [30,31] have demonstrated that under optimal operating conditions, high-load hydrogen high-pressure direct injection (HPDI) can achieve comparable efficiency to traditional diesel engines.

The adoption of hydrogen HPDI also endows the engine with exceptional flexibility in operation, owing to numerous tuneable parameters, such as injection pressure, injection duration, ignition timing, and injector orientation. The optimization of these parameters allows fine-tuning of the engine's performance to meet specific requirements. As a result, hydrogen HPDI presents a promising avenue for realizing efficient and versatile hydrogen-powered internal combustion engines, exhibiting the potential to rival conventional diesel engines. Further exploration and optimization of this approach hold substantial implications for the future of sustainable transportation and energy systems [10].

Figure shows the illustration of DI [7]:

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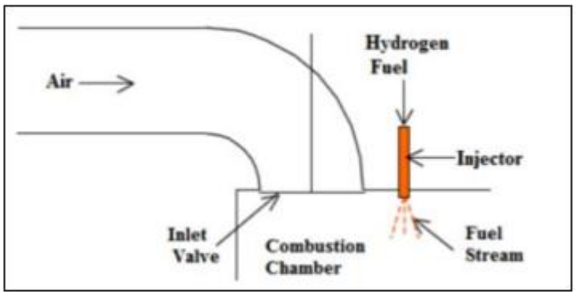


Extensive investigations into hydrogen direct injection systems have substantiated their superiority in terms of efficiency and adeptness in resolving challenges relative to other hydrogen delivery approaches. Notably, this method encompasses two distinct techniques, as scrutinized by a limited number of researchers: the 'Glow-Plug-Assisted Ignition' and the 'Spark-Assisted Ignition'. These advanced ignition techniques offer promising avenues for optimizing the combustion process and unlocking the full potential of hydrogen as a clean and efficient fuel source [10].

c) Glow-plug Technique:

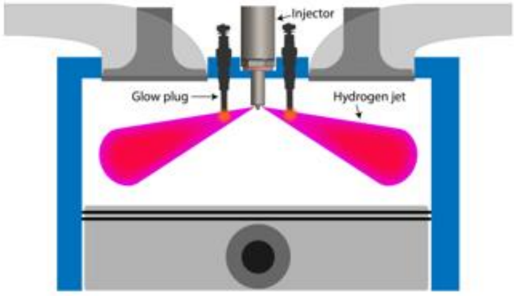
The glow plug, a device incorporating an electrically heated surface inserted into the engine combustion chamber, serves as a familiar component in diesel engines, facilitating cold starts by elevating the local charge temperature. In the context of hydrogen direct injection internal combustion engines (DI ICE), as depicted in Figure, the glow plugs necessitate continuous operation to ensure consistent hydrogen ignition in each engine cycle. Previous studies have documented the requisite glow plug surface temperature, ranging between 1200 to 1400 K [32,33,34].

In a pivotal study from 1979, Homan [31] established the glow plug as a more dependable ignition source for hydrogen, revealing a brief and stable delay of 10◦–13◦ crank angle (CA) between the start of injection (SOI) and ignition in a cooperative fuel research engine operating at 1240 rpm and a compression ratio of 18. In comparison, a multi-strike spark plugs ignition system (2.5 kHz strike rate) exhibited a fluctuating delay of 0–25◦ CA between injection and the initial pressure rise. Homan et al. [31] attributed this variation to the relatively smaller surface area of the spark gap when contrasted with the glow plug.

A subsequent investigation [34] highlighted that the glow-plug ignition approach incurred approximately 10% increased specific fuel consumption relative to diesel operation. For instance, at 5 bar IMEP (indicated mean effective pressure) and 1200 rpm, the indicated thermal efficiency (ITE) decreased from approximately 47% to 42%. Although NOx emissions were lower than those observed in diesel operation, they remained significant, particularly under high load conditions (>500 ppm) [34]. It is essential to acknowledge that these findings were derived from early research conducted several decades ago.

However, commercial applications of the glow-plug ignition technology have been limited due to concerns regarding the durability of the glow plug under the demanding conditions imposed by the high surface temperatures. As a result, recent engine development endeavours have rarely adopted this approach [35]. Despite these challenges, the concept of glow-plug-assisted ignition in hydrogen DI ICE continues to offer valuable insights and avenues for further research, potentially contributing to the advancement of efficient and environmentally friendly internal combustion engines.

Figure depicts the glow plug assisted ignition of hydrogen direct injection [10]:



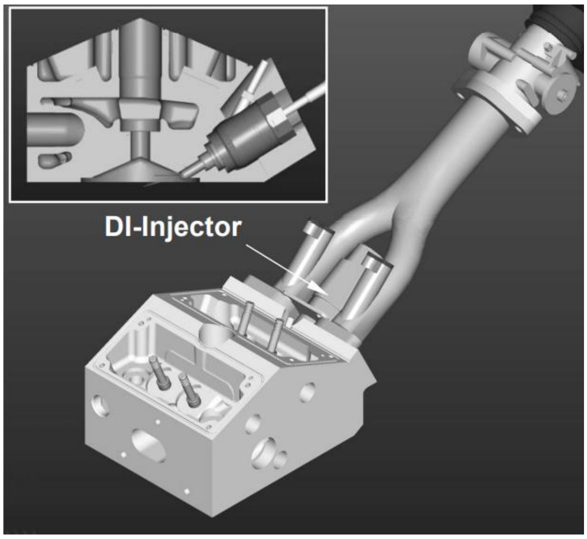
d) Spark-assisted technique:

Extensive literature on spark-assisted hydrogen direct injection (DI) combustion engines abounds, establishing this combustion concept as the most thoroughly investigated approach for hydrogen DI. While Verhelst [18] reviewed the progress of hydrogen spark-assisted ignition engines up to the year 2013, this review will focus on select highlights and recent developments. The prevailing engine configuration closely resembles that of the glow-plug-assisted ignition, as depicted in Figure 2, wherein the glow plugs are substituted by one or more spark plugs.

Numerous research endeavours have encountered limitations in the arrangement of injectors and spark plugs due to the constraints imposed by the geometry of production cylinder heads used for modifications. For instance, Wimmer et al. [36] converted an automotive-sized, single-cylinder spark-ignition (SI) engine into a hydrogen DI engine, achieving an indicated thermal efficiency (ITE) of 40% at low and medium loads, with only marginal inferiority compared to the state-of-the-art light-duty diesel engines prevalent at that time. An integral finding was that injection timing exerts a direct influence on mixture homogeneity, a factor that bears a more substantial impact on engine performance and emissions than ignition timing.

These investigations signify the immense potential of spark-assisted hydrogen DI combustion engines, offering valuable insights into optimizing engine design and operation. The quest for enhanced efficiency, reduced emissions, and sustainable propulsion drives ongoing research efforts, forging a path toward realizing the full potential of hydrogen as a clean and viable energy carrier in transportation.

Assembly of H2-DI-Injector shown in the figure as researched by Wimmer [36]:



e) **Recent Progress and Development Worldwide**

- In Delhi, India, the successful deployment of 15 hydrogen-fuelled three-wheelers (rickshaws) was achieved as part of a noteworthy pilot project conducted under the auspices of the United Nations Industrial Development Organization (UNIDO). This collaborative effort was co-funded by the International Centre for Hydrogen Energy Technologies (UNIDO-ICHET), the Indian Institute of Technology - Delhi, Air Products, the Indian Trade Promotion Organization (ITPO), and Mahindra & Mahindra, who served as project partners.

Among the fleet of vehicles, 10 were designated for passenger transport, while the remaining 5 were utilized for carrying loads. The original single-cylinder, air-cooled, carburetted bi-fuel gasoline/compressed natural gas (CNG) engines underwent a conversion process to enable electronically controlled port fuel injection (PFI) hydrogen operation, utilizing relatively lean mixtures to mitigate the risk of backfiring.

Remarkably, the transition to hydrogen operation resulted in a substantial reduction in all pollutant emissions, especially when compared to the original carburetted engines operating without any aftertreatment. These notable emission reductions underline the environmental benefits and potential of hydrogen as a clean and sustainable alternative fuel for transportation, fostering progress towards a more environmentally conscious and emission-free mobility landscape in urban areas like Delhi [37].

Figure below shows the Autorickshaw:

- The H_2ICE Project, an ambitious undertaking launched in 2021 and financially supported by the esteemed Horizon 2020 program of the European Union, was a trailblazing initiative with a focused objective: to illuminate the feasibility of adopting hydrogen-fuelled internal combustion engines in heavy-duty vehicles. This visionary endeavour centered on the retrofitting of conventional diesel engines, ingeniously enabling their seamless operation with hydrogen as the primary fuel source. The overarching mission of the project encompassed two vital facets: firstly, the substantial reduction of deleterious emissions to improve air quality and abate the environmental impact of transportation, and secondly, the promotion of widespread acceptance and seamless integration of hydrogen as a sustainable and ecologically friendly alternative to conventional fossil fuels within the transportation domain.

- The core ambition of the H_2ICE Project revolved around an in-depth exploration of the application of hydrogen-powered internal combustion engines in heavy-duty vehicles, aiming to usher in a profound transformation towards eco-conscious mobility solutions. In full alignment with the European Union's commitment to propagate sustainable and environmentally friendly technologies within the transportation sector, the project's implications extended far beyond its immediate scope. As a result, the outcomes and invaluable insights gleaned from this pioneering initiative hold the promise of redefining the landscape of heavy-duty vehicle propulsion, while concurrently wielding the potential to exert significant influence over policy decisions, steering them towards fostering a cleaner and more sustainable transport ecosystem not only in Europe but also resonating globally. **Figure below displaying history and current R&D [38].**

- Reliance Industries Limited (RIL) has proudly introduced a groundbreaking advancement: India's inaugural Hydrogen Internal Combustion Engine (H2ICE) technology for heavy-duty trucks, inaugurated by the esteemed Prime Minister, Narendra Modi, at the restigious India Energy Week in Bangalore. Promising an era of eco-friendly transportation, these H2ICE-powered trucks will emit remarkably low levels of emissions, while delivering performance at par with conventional diesel trucks. Additionally, they will reduce noise pollution, a feat that underscores the heralding of a greener future for mobility. Notably, the projected decline in operating costs further solidifies their potential to redefine the landscape of sustainable transportation. Driven by an unwavering commitment to a Net Carbon Zero vision, Reliance collaborates with Ashok Leyland, its esteemed vehicle partner, along with other technical allies, in the year-long endeavour to develop this unique technology. The fruit of their labour emerged in early 2022, with the engines roaring to life. Looking ahead, Reliance diligently prioritizes extensive testing and validation of the H2ICE technology for heavy-duty trucks,s ensuring their utmost reliability before embarking on their maiden commercial deployment across their captive fleet on a large scale. In parallel, Reliance ardently pursues the opportunity to craft a

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comprehensive end-to-end Hydrogen ecosystem for mobility, envisioning a holistic solution for sustainable transport [39].

- In this epoch of progress and innovation, Reliance weaves a compelling narrative that celebrates green mobility, leaving an indelible mark on the future of transportation and environmental conservation.

Figure depicting the H2ICE truck [39]:

- Tokyo City University played an integral role in the research that led to the demonstration of two hydrogen vehicles. In the report by Iwasaki [40], they detail the conversion of two engines to turbocharged Port Fuel Injection (PFI) operation, powered by hydrogen. These engines were integrated into a light-duty truck, equipped with a hybrid powertrain that utilized electric drive to enhance low-speed torque, and a 'microbus.' Remarkably, the 'microbus' successfully operated for over two years, covering an impressive distance of more than 15,000 kilometres by the time of publication (although it was decommissioned in March 2013, according to personal communication).

Both vehicles underwent testing using the JE05 test cycle, and the results were remarkable. Their NOx emissions fell significantly below the stringent Japan Post New Long Term Regulation requirements. The authors invested substantial effort in devising strategies to prevent abnormal combustion, especially backfire, primarily by implementing changes to the ignition system. This meticulous approach to addressing combustion challenges further exemplifies the dedication and commitment shown by the researchers in advancing hydrogen vehicle technology [40].

Figure below shows the bus and the light duty truck [40]:

4. Conclusion

Amidst the burgeoning pursuit of sustainability, diesel and gasoline engines are on the verge of being surpassed by a superior alternative, namely, H2ICEs (Hydrogen-fuelled internal combustion engines), as expounded in this paper. This transition marks a commendable stride towards achieving the noble objective of mitigating CO2 emissions and minimizing the carbon footprints attributed to automotive vehicles. The trajectory of hydrogen as a primary fuel in vehicles holds immense promise in the foreseeable future, provided that the requisite precautions are meticulously observed.

However, it is imperative to acknowledge that safety remains an integral concern and potential challenge in this domain. As previously discussed in the paper, one conceivable solution to address storage issues is the direct injection of hydrogen post-electrolysis, thereby simplifying the intricacies associated with fuel cells. Nonetheless, while this notion presents its advantages, it warrants further investigation and comprehensive study to ensure its efficacy and viability.

As the wheels of research and progress continue to turn, it is this ongoing exploration and scrutiny that will pave the way for a transformative and sustainable transportation landscape.

Notable outcomes of this study:

1) The emergence of H2 internal combustion engines in stills a glimmer of hope in our fight against global warming and local pollution when juxtaposed with traditional gasoline and diesel engines.
2) Hydrogen possesses the inherent capability to be utilized in Spark Ignition (SI) engines, whether integrated into existing systems without any alterations or modifications.

3) Innovatively departing from conventional storage methods or fuel cell usage, Hydrogen can be directly supplied into the engine immediately after the process of electrolysis.

Conflicts of interest
The author has no competing interests to declare that are relevant to the content of this article.

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