Hydrogen in General Aviation for an efficient and sustainable future

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Contents

Abstract

As global climate change accelerates, the aviation sector faces increased urgency to reduce carbon emissions in pursuit of the global goal of Net Zero 2050. Hydrogen has emerged as a promising fuel for future green aviation, offering high energy density per unit mass and virtually zero carbon dioxide emissions. The study examines two major pathways of hydrogen implementation in general aviation: combustion in piston engines and hydrogen fuel cells. Within combustion systems, both spark-ignited and compression-ignited (by using a kerosene jet) engines are analyzed, their pros and cons. The challenges they encounter are also addressed, including premature ignition, NO_x emissions, and backfiring. Hydrogen fuel cells are evaluated efficiency across varying load conditions and operating temperatures, cooling systems, and long-life spans. At the same time, major drawbacks, including weight, storage limitations, and design complexity, are also accounted for. Hydrogen use in internal combustion chambers shows a practical short-term solution as it has a high technology readiness level and requires minimal modifications to existing engines. On the contrary, Hydrogen fuel cells hold the most promising future, but are hindered by current technological barriers. The study presents a detailed comparison chart between internal combustion engines (ICE) and Hydrogen fuel cells, including efficiencies, emissions and complexity. Finally, the study concludes the importance of hydrogen in green aviation, while highlighting the need for infrastructure development and innovations in hydrogen storage.

1 Introduction

Global Warming's trend has currently been faster than any recorded in human history [1]. To resolve this serious problem, Net Zero 2050 has been proposed, which is a global goal initiated by the International Energy Agency (IEA) to reduce and neutralize greenhouse gas emissions (GHGs) to net zero by 2050 [2]. Transportation is a significant sector to neutralize, primarily commercial and general aviation. To achieve this goal, the Aviation sector has diversified its fuel source, aiming to reduce CO_2 emissions, although high costs must be considered due to safety aspects and certification efforts. Hydrogen, the fuel of future, is one of the diversified green fuels. Furthermore, Chapter two ("Is hydrogen a proper energy storage for GA?") evaluates Hydrogen's advantages and current challenges. Currently, two major pathways of hydrogen use have been developed: Combustion, in which fuel is combusted either in gas turbines or Internal Combustion Engine (ICE), and Hydrogen fuel cells, in which hydrogen is converted to electrical energy to power the aircraft. The objective of this paper includes an analyzation of Hydrogen as a fuel, an overview of both pathways for application in general aviation, analysis of each advantage and disadvantage, and an in-depth comparison between the two pathways.

2 Is hydrogen a proper energy storage for GA?

Hydrogen, an energy carrier, is free of CO_2 emissions while holding about three times the energy content per unit mass than conventional jet fuel, proving itself to be the fuel of the future [3]. This high energy density makes hydrogen a compelling candidate for aviation, although overall efficiency depends on the conversion technology used while emitting zero CO_2, undoubtedly being an essential source of energy for aviation [4]. Although hydrogen holds the highest energy content per unit of mass, its unit volume is significantly lower in the gaseous state under standard temperature and pressure (STP) [5]. Acknowledging that even the volumetric energy density for liquid hydrogen is 8MJ/L compared to conventional jet fuel of 32MJ/L, gaseous state hydrogen requires a significant volume of storage. Although gaseous hydrogen can be compressed to high pressure, the compression ratio and temperature of Hydrogen are proportional. Compression makes H_2

hot during fast refueling, which is compensated as stations precool gas hydrogen and keep the tank temperature below or equal to 85 °C[6]. Despite the advantages of Hydrogen, the storage space and weight balance of hydrogen invoke a significant design challenge in hydrogen powered aircrafts [5].

3 Hydrogen in Piston Engines

One of the pathways is combustion, which involves fuel being injected into the ICE, generating mechanical power that can be converted into thrust via a propeller. Combustion is the standard model for general aviation aircraft, for instance, the DA42. This approach substitutes conventional jet fuel with liquid or gaseous Hydrogen, requiring minimal modification to the aircraft piston engine [7]. There are two pathways of H_2 combustion: the spark-ignited engine and the combustion-ignited engine (Dual Fuel). Currently, there are two ways to ignite Hydrogen: either by using a spark-ignited engine or by injecting a small amount of jet fuel into a compression-ignited engine to initiate combustion, allowing hydrogen to be co-combusted.

3.1 Spark Ignited Engines

A typical Spark Ignited Engine (SIE) gasoline mixes fuel (typically AV Gas for application in GA) and air prior to the combustion process. Then the air-fuel mixture gets injected into the cylinder and is ignited by the spark plug. Under conventional spark-ignited engines, Hydrogen can combust at very lean equivalence ratios, well below those of conventional AVGAS-air mixtures, enabling ultra-lean combustion with lower flame temperatures. This results in lower heat transfer to the walls, higher energy efficiency, and lower NOx and PM emitted [8]. One significant advantage the Spark Ignited Engines pathway holds is that it substitutes the conventional AV-gas with Hydrogen, thus allowing it to function with some modifications. Emissions of hydrocarbons and CO_2 are virtually negligible because the only byproduct of the combustion is water vapour (H_2O). Nevertheless, due to the higher combustion speed of Hydrogen and high flame temperature,

spark-ignited engines emit NOx and PM. The ignition delay using Hydrogen is shorter than conventional AV-gas while holding a higher combustion temperature, resulting in an increased risk for backfiring [9]. Despite a critical advantage of a spark-ignited engine is that it can ignite lean mixtures, it comes with drawbacks simultaneously, as the hot gases and hot spots on the cylinder can serve as ignition sources, causing premature combustion and flashbacks [10].

3.2 Compression Ignition Engines [Dual Fuel]

A typical Compression ignition engine (CIE) doesn’t have a spark plug, and the mixture of air and diesel or jet fuel ignites due to the compression in the cylinder. During Stroke one, only the hot compressed air is drawn into the cylinder to get compressed. As the air is compressed during the second stroke, the internal temperature rises, and the heat is used for the ignition and burning of the fuel. At the end of the compression stroke, the high-pressure fuel is directly injected into the cylinder to be ignited by the heat of compressed air [11]. Due to a small amount of hydrogen injected into the cylinder periodically, it improves the homogeneity of the mixing in the diesel spray system, mainly due to the high diffusivity of hydrogen. Due to this process, the formation of hydrocarbons, carbon monoxide, and carbon dioxide can be significantly reduced, depending on the hydrogen substitution rate and combustion conditions [8]. However, Compression ignition engines can not operate solely on hydrogen as the compression temperature is insufficient for initiating combustion due to a higher autoignition temperature required [7]. A solution to this problem is to operate on a dual-fuel engine. By using conventional jet fuel as a pilot fuel for take off and landing between 10-30% of total fuel, hydrogen can still remain the primary fuel for cruise power. Similar to the spark-ignited engine, NOx emission is also a central problem in combustion-ignited engines. Austro Engine prompted a hydrogen dual fuel model involving using conventional jet fuel as its pilot fuel. The test bench results indicate a 90% energy substitution rate, 99% of CO reduction, and 89% of CO_2 emissions. However, under part load, 1690 RPM, 10 Bar IMEP, the maximum hydrogen energy share is limited to 60% by knocking, and it could potentially exceed the maximum allowed cylinder pressure [7].

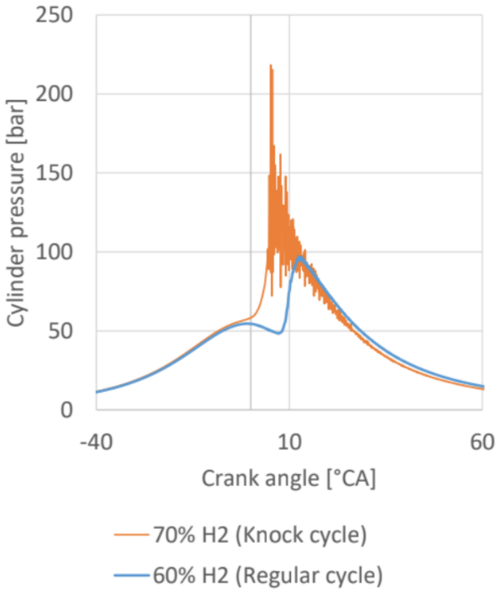

Figure 2: Line graph showing the cylinder pressure of Combustion ignition engine using 60% of H2 and 70% of H2. [7]

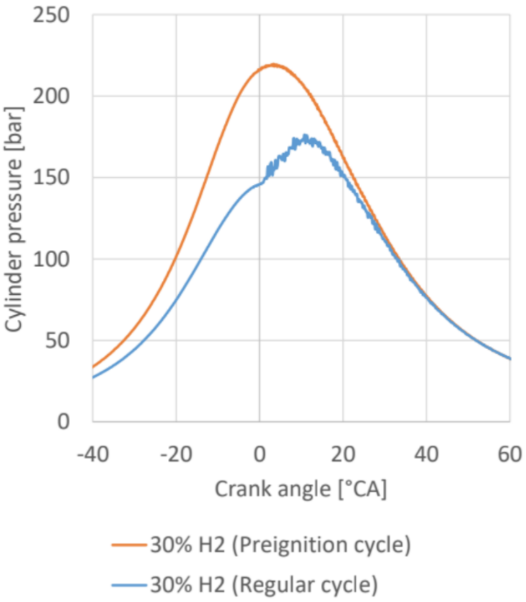

Figure 3: line graph showing the cylinder pressure of Combustion ignition engine using 30% H_2 in preignition cycle and regular cycle [7]

To improve the engine, Astro engine modified the engine by injecting liquid H_2O directly into the cylinder, thus reducing the temperature significantly while increasing H_2 substitution. This model increases boost pressure, resulting in more mass of air being induced. This causes hydrogen to be less sensitive, thus reducing the risk of premature ignition. Exhaust gas recirculation was also implemented as it put exhaust air into the cylinder, thus reducing the temperature, resulting in a lower risk of premature ignition while having the exhaust gas recirculation. Another aspect is a significant reduction in compression ratio. However, by changing the piston to a bowl shape, adapting the rings/linear system, and enhancing cylinder cooling, the engine can perform better with hydrogen [7]. A major drawback of this model is the decrease in the AFR, which greatly increases the likelihood of abnormal combustion and limits the hydrogen energy share. The data shows the energy share of hydrogen at different load points, with the triangle indicating the potential energy reached after injecting water into the cylinder [7].

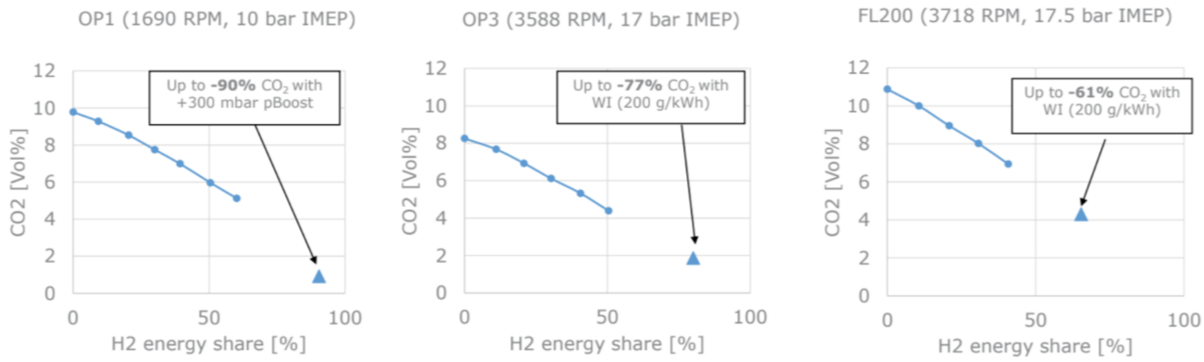

Figure 3: Three data graphs showing the percentage energy share of Hydrogen with triangle indicating the potential energy share of Hydrogen under liquid water. [7]

Spark ignition engine and combustion ignition engine are the two sub-pathways of ICEs; they require less modification, being less complicated. Nevertheless, they are currently being held back by NOx emissions, premature ignition, and engine backfiring.

4 Hydrogen Fuel Cell

Hydrogen fuel cells, a stack that creates electricity through an electrochemical process, are excellent devices for electric aircraft. A fuel cell is composed of an anode, a cathode, and an electrolyte membrane. At the Anode, hydrogen is broken down into protons and electrons. The electron flows through the circuit to generate electrical power for the aircraft, while the proton will combine with oxygen to create the only byproduct, water [12].

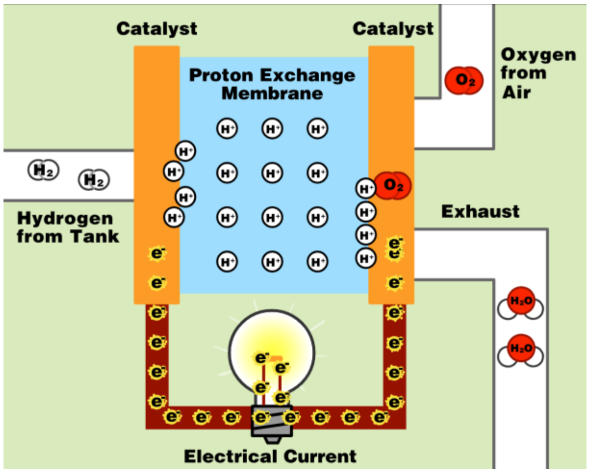

Figure 3: Diagram showing the process of fuel cell [13]

Hydrogen fuel cells undergo zero combustion process, resulting it emitting completely no emission despite water vapour. However, hydrogen fuel cell exhibits vary efficiency depending on the load conditions. At moderate load, fuel cell can operate at maximum efficiency. Whereas under part load or overload conditions, efficiency decreases due to factors like increased loss of auxiliary component. This trend underscores the importance of high load condition operating on fuel cell. [14]

Effective thermal cooling is also vital for hydrogen fuel cells. Fuel cells generate heat during operation, thus requiring an effective cooling system, as the performance of certain fuel cell (low temperature PEM fuel cells) presents an inverse relationship with the rise in operational temperature. The cooling system must be maintained to ensure the longevity and efficiency of the fuel cell [14].

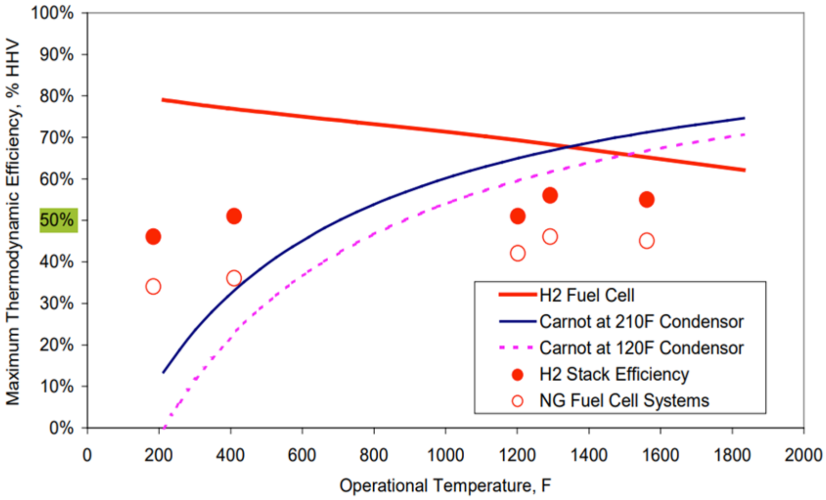

Figure 4: Hydrogen Fuel cell efficiency shown under different temperature [15]

The Cooling system in a hydrogen fuel cell can vary: air cooling, liquid cooling, and evaporative cooling [16]. Each cooling system has its own unique advantages and is chosen based on the specific requirements of the designated application.

Aside from temperature and load condition, the purity of hydrogen also directly impacts the fuel cell performance. Impurities could poison the catalyst, reducing efficiency and increasing the risk of system failure [17].

Various factors, including operating conditions, maintenance, and quality of hydrogen fuel, determine Fuel cell lifetime. Under optimal conditions, proton exchange membrane (PEM) fuel cells can achieve a lifespan exceeding 5,000 hours [18].

Efficient scaling could allow fuel cell systems to increase their size or number to meet the higher demand for power. However, this process requires system integration, cost, and performance assurance. Strategies such as modular system design and advanced thermal management techniques can mitigate the complexity and difficulties of efficient scaling [15].

Although fuel cell holds advantages that surpass hydrogen use in ICE, the weight and complexity remain a huge obstacle. Unlike combustion, hydrogen fuel cells require a new model to be designed. Weight, one of the four principles of flight, is especially critical in aircraft design. Fuel cell systems, including an electrical motor, may be heavier than ICE, resulting in increased complexity in aircraft design [19]. An excellent aircraft design prioritizes lower complexity and lighter weight while achieving all requirements. A heavier weight results in more lift and thrust needed, which results in burning more fuel while being limited to travel at a shorter distance [20]. Aside from weight, Fuel-Cell aircraft typically use two cooling system: one holds the stack around 60-80 °C, and a separate one keeping the motor around 100 °C. However, Liquid Hydrogen is not a cooling loop: It is stored at -253 °C in an insulated tank and warmed by heat-exchanger prior to usage, separated from the coolant [21]. The cooling and the weight and complexity of fuel cells are the main drawbacks in the development of fuel cell aircraft [8].

5 Comparison

	Hydrogen Combustion -Spark Ignited Engine	**Hydrogen Combustion -Combustion Ignited Engine (Dual Fuel with jet fuel)**	**Hydrogen fuel cell**
CxHy, CO, CO_2 emissions	Virtually Neglectable [8]	99% CO reduction 89% CO_2 reduction [8]	Completely eliminated [12]
NOx emissions	Around 63.7 mg/kWh [22]	Similar level to Sparked Ignited Engine, reduced 57.94%-68.25% compared to kerosine in aircraft turbofans [23]	Completely eliminated [12]
Water Vapour	2.55 times more water vapour in flight than kerosene aircraft [23]	Same trend, significant increase of water vapour compared to kerosene aircraft [23]	Depend on Load condition. Generally lower than SIE and CIE [14]
PM emissions	Low level, negligible compared to gasoline ICE [8]	Very low [8]	Completely eliminated [8]
Efficiency	45% [24]	47% [25]	40-60% [26] Average/Future
Weight	Minimal modification to original aircraft, minimal additional weight, minor system adjustment needed [27]	moderate modification due to dual-fuel tank system [27]	Heavier weight due to separate hydrogen tanks, humidifiers, compressors and cooling system [28]
Complexity / cost	Minimal modification Low complexity/ Moderate Cost, mostly reuse of ICE designs with minimal adjustments [29]	Moderate modification Moderate complexity/ Moderate Cost, requires dual fuel system and safety system [30]	Require specific new design Electrical panels High complexity/ High cost l, require new design, advanced cooling system [31]
Technology Readiness level	High, already demonstrated test bench results validating ICE hydrogen engine [32]	High, dual-fuel hydrogen prototype developed and tested [7]	Low, only small prototypes flying TRL level 3 [33]

Table 1: Table demonstrating the comparison between Sparked Ignited engine, Combustion Ignited engine, and fuel cells.

Regarding the comparison between direct combustion, either SIE or CIE, and fuel cells, each has different advantages and disadvantages. Direct combustions require modification, maintaining low complexity and a higher technology readiness level [7]. Although their emissions are higher than those of fuel cells, they are more practical in the short term as they can be quickly implemented with minimal adjustments to current aircraft models. On the other hand, fuel cells offer the most promising performance in terms of efficiency and zero-emission operation, but it is faced with barriers due to weight and space balance, high complexity, and a lower technology readiness level. However, acknowledging the difficulties of fuel cells, fuel cell aircraft had already been created and proven successful, for instance, the HY4 from H2FLY in 2023. HY4 is the world's first piloted hydrogen fuel cell aircraft powered by liquid hydrogen for energy supply [34]. As fuel cell technology's readiness level gradually increases, they could potentially surpass hydrogen use in ICE aircraft.

6 Conclusion

This study aims to present an overview of the two main pathways for Hydrogen use in General Aviation, explain the advantages and disadvantages behind each pathway, and finally, compare the two major pathways. The study presented a Spark Ignited engine, highlighting the advantages of low ignition energy, and low equivalence ratio. Showing the potential of the Spark-ignited engine to engage in an ultra-lean combustion process, which increases energy efficiency and lowers NOx and PM emissions. Despite the advantages of the Spark Ignited Engine, the potential hazard of and backfiring has been a major downside of SIE. The study examined a combustion-ignited engine as a dual-fuel engine due to hydrogen's initial compression temperature not meeting demand, requiring 10-30% conventional jet fuel as pilot fuel. The study further analyzed the weight and complexity of the fuel cell with hydrogen's storage difficulties. The study then concludes by comparing the emissions, efficiencies, and complexities of the two pathways, finding direct combustion as the most practiced in the short term while fuel cells hold the best potential. Hydrogen, with its ability to cut CO_2 emissions by almost completely while providing high energy, will undoubtedly become the fuel of the future, which will guide the future of green aviation. However, despite its potential, challenges include volumetric energy density, cryogenic storage for liquid hydrogen, high-pressure tanks for gaseous hydrogen, and the lack of refueling infrastructure at airports must be addressed prior to mass adoption. The development of a robust model of hydrogen storage and refueling infrastructure is essential for Hydrogen aviation in the future.

Acknowledgements

I would like to thank Dr. Felix Zahradnik for all the support throughout writing this paper.

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Table of Abbreviations

Abbreviation	Definition
AFR	Air-Fuel Ratio
Av Gas/ AVGAS	Aviation Gasoline
CIE	Compression Ignition Engine
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CxHy	Hydrocarbons
GA	General Aviation
GHGs	Greenhouse Gases
H_2	Hydrogen
H_2O	Water
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMEP	Indicated Mean Effective Pressure
MJ/L	Megajoules per Liter
NOx	Nitrogen Oxides
PEM	Proton Exchange Membrane (fuel cell)
PM	Particulate Matter
RPM	Revolutions Per Minute
SIE	Spark Ignition Engine
STP	Standard Temperature and Pressure
TRL	Technology Readiness Level