Advanced development of hydrogen engines for diverse transportation

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Abstract. The hazard of conventional fossil fuels that transportation relies on nowadays has urged the scientific community to speed up the process of diminishing the pollutants caused by daily transportation and finding an opulent energy source for its superstition. Renewable resources and hydrogen are deemed as the next generation resource. However, hydrogen is the ultimate choice for transportation for its excellent performance both in the fields of environmental protection and energy. In this article, a study on the global production of hydrogen is performed, delving into the present conditions of the hydrogen industry. The principles referred to when choosing hydrogen to be an energy source for various transportation are discussed, and a comparison between conventional fuel engines and hydrogen fuel engines is made. The existing technical problems concerning the application of hydrogen engines or hydrogen fuel cells are reviewed. Combined with the usage of technologies on hydrogen, an envisage of future clean transportation is demonstrated.

Keywords: hydrogen engine, fuel cell, transportation, internal combustion engine.

1. Introduction

With the advent of the industrial revolution, there has been an uprising hankering for the fuel needed. However, over 80% of the global energy demand is covered exclusively by fossil fuels, formed from organic bodies buried deep beneath the earth through extreme pressure and inestimable time. Hence, fossil fuel like petroleum is classified as a non-renewable resource. With the incessant development of civilization and technology, the notion of sustainable development is widely accepted. Fossil fuels are now not as preferred as they used to be in the 1900s concerning the fact of global warming and other problems pertaining to environmental protection [1]. Thus, an outcry for a new combustible energy resource has risen. There has been a trend to electrify the engines and claim that solar power and wind power will eventually supersede internal combustion (IC) engines, without giving any consideration to the battery, whose production does more harm to the environment, however [2, 3]. A new proposal put forward is to use hydrogen instead. It is opulent and easy to produce, while the combustion of hydrogen and oxygen does not harm the environment at all since the production is merely water. Besides, hydrogen does have a very high caloric value, three times that of gasoline. This means it is more efficient for hydrogen regarding volumetric and gravimetric energy storage density [4].

Nevertheless, to make it widely adopted by the manufacturers of hydrogen engines, the storage issue is a major technical barrier that has to be encountered. While using cryo-compression is a feasible

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approach to storing hydrogen and has been tested in prototype vehicles, engines feeding on hydrogen fuel cells have been in mass production [5]. Besides on-land automobiles and maritime vessels, according to Boeing's commercial market outlook, it is projected that the number of the global fleet will at least double, reaching more than 48,500 jets during the forecasted period from 2023-2042, which can generate enormous greenhouse gas emissions and detrimental pollutants. Although many different fuel types are available, kerosene is the most used for its lowest price in aviation, comprising 35% alkenes, 60% cyclic alkanes, and 15% aromatics. Despite its cheap price, it releases different greenhouse gas (GHGs) emissions after participating in combustion and thus harms the environment, let alone the sulfur oxides, NOx, and other contaminants. Hence it is also a better fuel for aviation [8].

Hydrogen and hydrogen fuel cell technologies will surely receive continuous attention from manufacturers and governments as promising options for energy transition and sustainable development. As can be imagined, hydrogen-powered engines, no matter for cars or airplanes, will become available for commercial or personal use in the foreseeable future. The article aims to present the present conditions of hydrogen engines' application and the technologies used in various transportation and to mark the challenges that must be overcome to propel the development of the technologies.

2. Feasibility and application principles of hydrogen engines

2.1. Production

Since the beginning of the 20th century, hydrogen has been used as a fuel [9]. Meanwhile, driven by the uprising demand for cheap hydrogen resources, scientists have already discovered different ways to produce hydrogen [9]:

2.1.1. Derive from hydrocarbon reforming. To derive hydrogen from hydrocarbon fuels, there are practically three major approaches: steam reformation, partial oxidation (POX), and autothermal reformation (ATR). The differences among them are shown in Table 1.

The gas steam produced during the reforming process mainly consists of hydrogen, carbon monoxide, and carbon dioxide [9]. Thus, the temperature of the steam has a solid requirement on the facility, and it also has to do with the following processes, which are intended to purify the hydrogen produced. Besides, the participation of oxygen at high temperatures can lead to severe equipment erosion. Since the product is mingled with mainly two kinds of byproducts, the production ratio, H_2/CO ratio, matters a lot as it determines the processes afterward and the final price of the hydrogen derived. Hence, steam formation is most used in the field of hydrogen production.

Table 1. Comparison of reforming technologies [12].

Process	Advantages	Disadvantages
Steam Reformation	Existence of industrial experience No participation of O_2 The lowest temperature during the process Best $\frac{H_2}{CO}$ ratio for the production of hydrogen	Much air emissions
Autothermal Reformation (ATR)	Process temperature is lower than POX Low methane leak	Lack of commercial practice Need participation of O_2
Partial Oxidation (POX)	Decreased desulfurization requirement No need for any catalyst Low methane leak	Low $\frac{H_2}{CO}$ ratio Highest process temperature Soot formation

2.1.2. Hydrogen from biomass. Recent years have witnessed a rise in the usage of biomass, no matter direct or indirect. Biomass is highly available, including animal wastes, municipal wastes, agricultural wastes and residues, and many other origins [13]. Since the energy transition efficiency is as low as 10-30%, even if the carbon dioxide is not counted because the carbon inside the biomass is from the environment, putting biomass into combustion is a waste of resources, and the combustion produces many pollutants like sulfur dioxide and smoke. So, it is not a proper way to support sustainable development. Besides, whether to gasification or liquefaction, biomass can only make use of partially its components. It is better to separate the hydrogen and carbon contained in biomass to meet a higher energy efficiency standard. The details of a biomass-to-hydrogen strategy are shown below. Pyrolysis is to apply heat to biomass until a condition under which a temperature of 650-800 K and a pressure of 0.1-0.5 MPa while vacuum is reached, then the conversion from biomass into liquid, solid, and gaseous products can be performed. The liquid products contain mainly oil and solid products, charcoal, while the gaseous compounds are mainly hydrogen and carbon oxides (1-3). To derive purified hydrogen, separation of the former products and steam reformation with the participation of water is required (Figure 1).

$$Biomass + Heat \rightarrow H_2 + CO + CH_4 + Other\ products \tag{1}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{2}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{3}$$

Besides, oil products can also produce hydrogen, as discussed in hydrocarbon reformation.

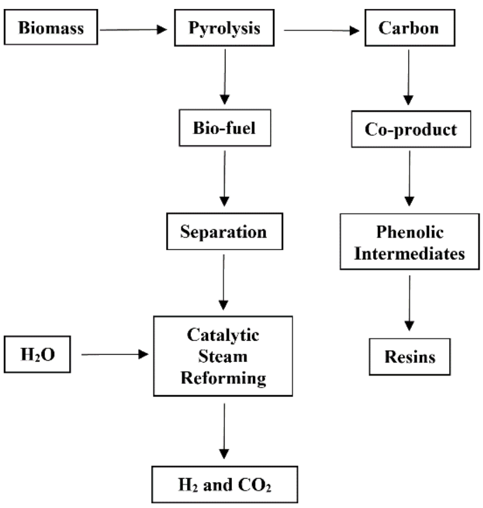

Figure 1. A typical pyrolysis strategy to convert biomass into hydrogen [12].

2.1.3. Hydrogen from water. Electrolysis is the easiest way to get high-quality hydrogen. It is also now commonly used in industry. System efficiencies of 56-73% can be achieved by commercially used low temperature electrolyzers [13]. Besides, thermochemical water splitting and photo-electrolysis are also ways to generate hydrogen. However, the overall principle lies below (4-6):

$$H_2O = H_2 + \frac{1}{2}O_2, \quad \Delta H = -288\ kJ \cdot mol^{-1} \tag{4}$$

$$Anode: 4OH^- \rightarrow O_2 + 2H_2O \tag{5}$$

$$Cathode: 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{6}$$

2.2. Storage

As the lightest gas formed with the smallest atoms, it is easy to compress its volume under the pressure of 350 bars or even 700 bars in tanks made of carbon fiber for hydrogen engines that provide power for automobiles. This storage technology has been commercially used in most cars with hydrogen engines or hybrid electric vehicles (HEV). For long-distance transportation or long-term storage, it is obviously better to liquefy the hydrogen because both need to lower the expenditures since transportation charges on the mass and warehouses charge on the volume – both require raising energy stored per unit. To liquefy the hydrogen, it is needed to reach 10-15 MPa for pressure and 50-70 K for temperature.

The higher heating value of hydrogen energy content is 141.8 MJ/kg at 298 K, while the lower heating value of it is 120 MJ/kg at 298 K, which is much higher than that of most fuels (e.g., gasoline 44 MJ/kg at 298 K) [15]. Once the hydrogen exudes in a closed space, when the percentage reaches between 4.0~74.2% (which are the lower flammability limit and upper flammability limit of hydrogen gas, respectively, since hydrogen cannot remain in the liquid state under the circumstances of standard temperature and pressure), there is a great possibility for explosion when encountered fire because of the high level of energy density. However, the authorities have published procedures and invented the facilities to ensure safety. It is foreseeable that in the future, hydrogen can be as safe as gasoline no matter if it moves on the wheel or stores in a tank. The USA Department of Energy claimed that hydrogen will gradually be on the same safety level as fossil fuels as more hydrogen demonstrations get underway [16].

3. The advanced application of hydrogen engines

3.1. On land for automobiles

3.1.1. Direct use. A comprehensive study on hydrogen internal combustion engines (H_2ICEs) up to that time has been published [17]. The overall principle of conventional and hydrogen engines are the same: injection, compression, ignition, and ventilation [18]. However, since the fuel has changed from fossil fuel to hydrogen, there are new requirements for the system. Firstly, for the injection system, a timed injection is necessary. After all, there is no need for on-land automobiles to store liquid hydrogen as the energy a compressed tank of hydrogen can carry is far beyond the demand, and it can be refilled at every gas station (if hydrogen is widely used). Since hydrogen has a low autoignition temperature, it is a prerequisite to keep the hydrogen away from the manifold as the vented gas could heat the manifold, and there are possibilities that the manifold can cause a backfire once it comes into contact with hydrogen. Hence, port injection and a delicate program are needed, or direct injection (DI) is used during the compression stroke. Secondly, the compression process requires an optimal compression as high as that of other fuels to increase the engine's efficiency. Compression ratios used in H_2ICEs can vary from 7.5:1 to 14.5:1 [19, 20]. Besides, the rather low ability for hydrogen to lubricate should be paid attention to. The lubrication of the piston and the axles should involve specially designed types of oil. Thirdly, the ignition system must be appropriately grounded, or the electrical resistance of the ignition cable must be changed to shun unwanted ignition because of the residual energy. Additionally, cold-rated spark plugs are recommended to avoid backfire while plugs that include platinum electrodes should not be used since platinum can be a catalyst for hydrogen oxidation. Lastly, positive ventilation is highly recommended to decrease the hydrogen concentration in the exhaust mixture to avoid backfires or even unsafe situations.

3.1.2. Indirect use. The other way to use hydrogen is to use fuel cells with an electric engine instead of IC engines; the details have been demonstrated in [21, 22]. This method of utilization can be a solution to cross the gap between fossil fuel and hydrogen. However, both require onboard hydrogen storage, while the former choice can be achieved through minor modifications of the existing electric cars that use only batteries. The categorization of fuel cells depends on the type of material the electrolyte used, which is between anode and cathode. Although there are different types of fuel cells available, the fundamentals are the same, which is exactly the opposite of water electrolysis. The chemical reactions inside a fuel cell are shown below (7-9), together with a schematic of the fuel cell itself (Figures 2 and 3):

$$Anode: H_2 \rightarrow 2H^+ + 2e^- \quad (7)$$

$$Cathode: {}^1/_2\, O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (8)$$

$$Overall : H_2 + {}^1/_2\, O_2 \rightarrow H_2O \quad (9)$$

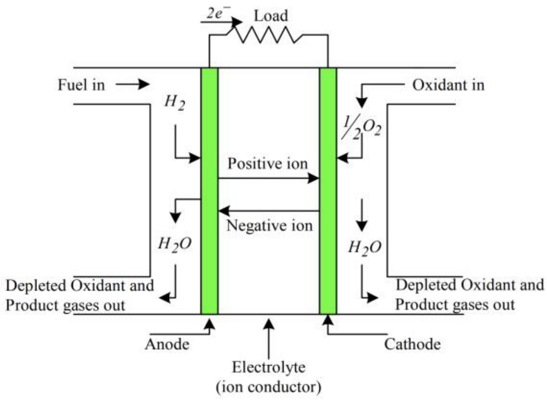

Figure 2. A diagram of fuel cell operation [23].

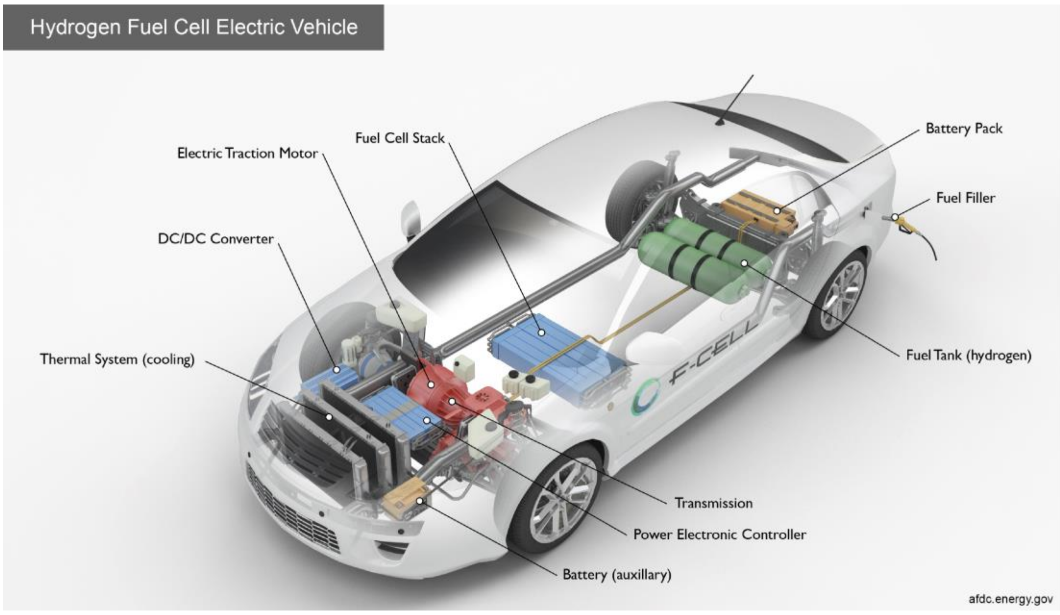

Figure 3. Automobile with hydrogen fuel cell and onboard hydrogen storage system [24].

3.2. Aviation

3.2.1. Direct use. In aviation, the commercial usage of hydrogen can be dated back to the 1900s when Luftschiffbau Zeppelin Gmbh built the LZ 129 Hindenburg. However, hydrogen has been put away from aviation after its disaster for decades. As a great producer of GHGs, experts have been thinking about using hydrogen again in aviation as a fuel. In 2022, the first airplane that operates only on hydrogen finished its maiden flight, and Europe announced that it would materialize the commercial usage of hydrogen aircraft before 2035.

However, for contemporary civil aviation, which is mainly subsonic, superseding jet fuel with hydrogen still needs to overcome several technical problems. Given the fundamentals of jet engines and

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the properties of hydrogen, the storage, the injectors, and the combustors should be modified [25]. Besides, due to the high temperature, NOx emission production is to be mentioned. To prevent flashback hazards, it is also recommended to flush the pipelines during the start and shut-down cycles of the engine. Multiple means of hydrogen storage have been introduced [26], while hydrogen injectors and combustors tested are included [27].

Furthermore, humans never stopped dreaming fast. With the development of technology, the concept of supersonic traveling is proposed again, and the usage of hydrogen ensures it. Together with hydrogen fuel and Turbine-Based Combined Cycle (TBCC) or scimitar engines, humans are closer to inaugurating supersonic travel or even the space-travel era (Figure 4).

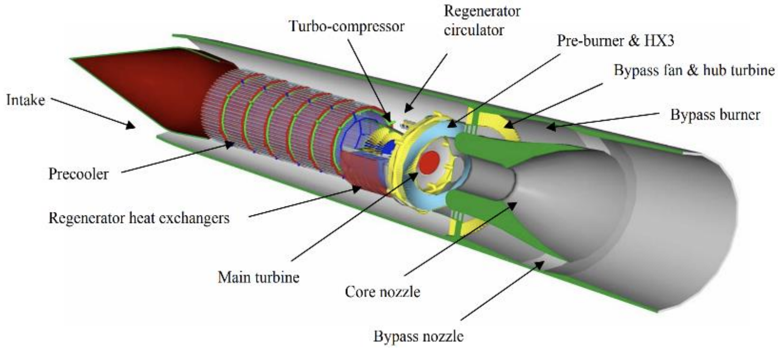

Figure 4. A schematic of a scimitar engine feeds on hydrogen power [28].

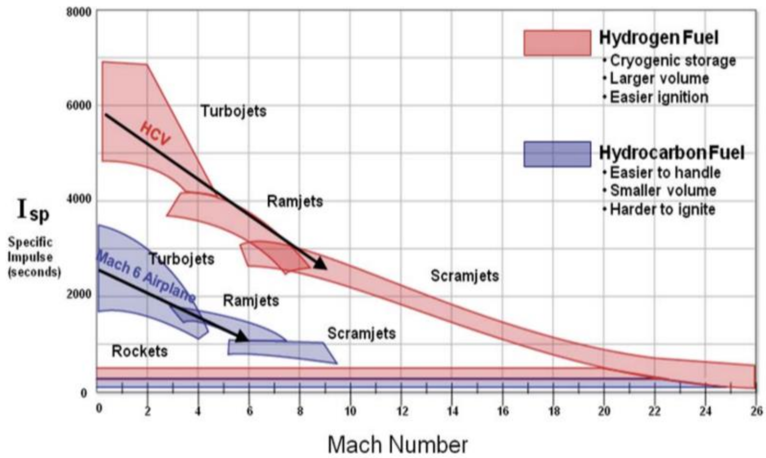

Figure 5. A chart demonstrating hydrocarbon versus hydrogen fuel [28].

Hydrogen fuels do not require any further construction of infrastructure, which reduces the cost of the transition from hydrocarbon fuels (Figure 5).

3.2.2. Indirect use. The rationale of the fuel cells remains the same, as discussed in the indirect usage of hydrogen in automobiles. Since the power demand for aviation is huge, hydrogen storage should be carefully considered, as aviation is sensitive to the mass carried. Several means of storage are presented [28]. However, the mass of the fuel cells an intercontinental passenger aircraft needs can be far beyond its capacity. However, the fuel cell system can be an electric energy source for anything other than propulsion, such as the auxiliary power unit (APU) or the air conditioner packs. Airbus and Boeing, the two dominating manufacturers in aviation, have already announced that they are endeavoring to make it fructified [29]. Detailed analysis and design of fuel cell systems on aircraft have been carried out concerning the loadout configuration and other characteristics [30].

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4. Conclusions

Compared to conventional fossil fuel, hydrogen has advantages and disadvantages when used in diverse transportation. This article emphasizes its property of no harm emissions after combustion or a chemical reaction, its higher density of energy, and its diverse derivation. However, the storage and transportation of hydrogen need to be closely monitored as it has a lower autoignition temperature. As for all kinds of transportation included in the article, hydrogen can either be a direct fuel of IC and jet engines or an indirect fuel that produces energy through fuel cells. Certain technical problems, including ignition control and backfire prevention, should be considered when used as a direct fuel. When used as an indirect fuel, minor adjustments should be made to the original electric vehicle (EV) or plug-in hybrid electric vehicle (PHEV) while in aviation, it is not powerful enough to propel jets but electrical systems onboard. Additionally, in the future, humans will be sure to inaugurate a new era of supersonic or even aerospace travel by using hydrogen technologies. Further problems pertaining to the design or configuration of the system will necessitate a quantitative study of the designated transportation models and other issues involved.

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