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Hydrogen, the future of aviation

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One of the biggest challenges of modern aviation is the development of technologies that reduce or eliminate emissions of harmful combustion components into the atmosphere. European authorities are imposing increasingly stringent emissions regulations. Therefore, new models of combustion chambers, new combustion methods, as well as new types of aviation fuels must be developed.
This article presents the possibilities of using hydrogen propulsion in aviation. The reasons for conducting research on hydrogen propulsion are discussed, as well as the history of the introduction of hydrogen propulsion into aircraft engines. Problems that can be encountered in the production and storage of hydrogen are identified and explained. Proposals for the use of hydrogen combustion or the use of fuel cells to power turbine engines are also presented, and the economic aspect of this type of fuel is discussed.

Key words: *combustion chamber, hydrogen propulsion, aircraft turbine engine, emissions, hydrogen*

1. Introduction

One of the most promising energy sources for aircraft engines is hydrogen. Alongside electric propulsion and batteries, these are two main contenders to achieve zero emission goal. The energy potential of hydrogen, as well as traditional fuels, surpasses that of batteries by a significant margin. In 2020, the costs associated with hydrogen were more than 20 times lower (in €/kWh) compared to Li-Ion batteries. Anticipated cost reductions in the upcoming years are expected to occur much more rapidly for hydrogen than for batteries. This trend may lead to costs reaching approximately 30 times less than the current expenses by 2025, providing hydrogen with an even more substantial advantage [20]. Hydrogen can provide zero carbon dioxide emission. Moreover, the possibility to burn leaner mixtures, significantly reduce emissions of nitrogen oxides, which are responsible for the destruction of the ozone layer, are largely responsible for smog, and have a devastating effect on plants and other living organisms [4]. Depending on the amount of carbon dioxide produced, hydrogen can be divided into gray, blue, and green. The term gray hydrogen refers to the situation when carbon dioxide is created during its extraction or production. In the case of blue hydrogen, pollutants are captured and stored. Green hydrogen is created only through renewable energy sources, when during the electrolysis process and during its combustion, only water is being produced [25]. Looking at the advantages of green hydrogen and the fact that it has a high heating value (2.5 times that of aviation kerosene) it is highly probable that it will become an excellent fuel for turbine engines. The use of hydrogen as aviation fuel, however, is not a new idea. Hydrogen was used as early as 1943 in the United States, during work on the space program, or with the use of hydrogen to power the B-57 bomber in 1956. Besides that, the Russians designed a hydrogen-powered Tu-154 aircraft (named Tu-155 after modifications) [3]. In addition, work on smaller projects was going on all the time. Figure 1 shows some of the most significant designs for the development of hydrogen propulsion, which confirm that hydrogen is still an attractive fuel in various aspects.

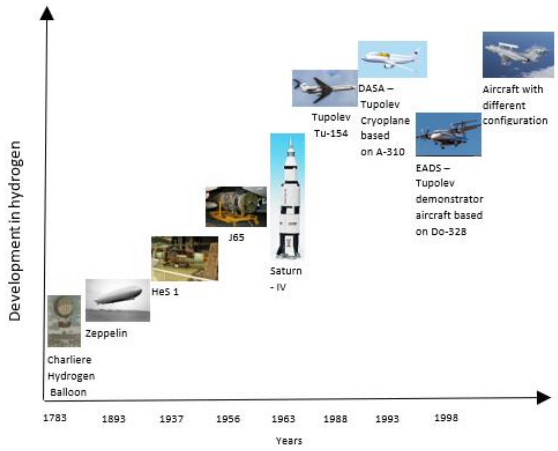

Fig. 1. Development of hydrogen propulsion over the years [15]

One of the most important issues in hydrogen propulsion is how to produce it. Three ways of producing hydrogen are the most popular: thermal dissociation, electrolysis using photonics, and bioenergy. Production can also occur using nuclear energy. Sources of hydrogen, according to 2013 data, are shown in Fig. 2. It can be noticed that: coke oven gases, fossil fuels, oils still play the largest role, but electrolysis is also used.

The properties of hydrogen are shown in the Table 1.

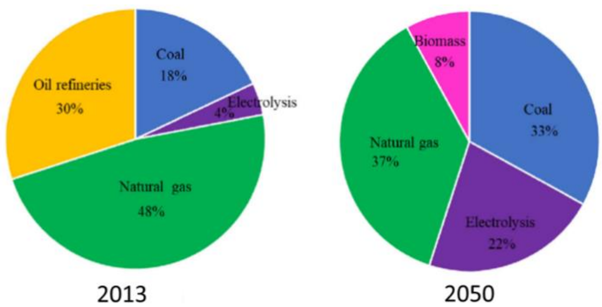

Fig. 2. Sources of hydrogen production with forecast [16]

Table 1. Properties of hydrogen and aviation kerosene [22]

	Hydrogen (LH$_2$)	Aircraft kerosene (Jet A)
Density [kg/m^3]	71	790
Energy density [MJ/dm^3]	10.03	36.66
Specific energy [MJ/kg]	141.8	46.4
Autoignition point [°C]	500	210
Flame temperature [°C]	2250	2230
LHV [kWh/kg]	33.3	11.9

The most economical way of production is certainly the use of fossil fuels. It uses one of three methods for this: steam reforming, auto-thermal reforming, and partial oxidation.

The most popular of these methods is the Steam Reforming Method (SRM), during which methane and steam, under the influence of an endothermic reaction, are transformed into hydrogen and carbon monoxide, as shown in equations (1)–(3).

$$CH_4 + H_2O + \text{heat} \rightarrow CO + 3H_2 \quad (1)$$

After further conversion, one gets:

$$CO + H_2O \rightarrow CO_2 + H_2 + \text{heat} \quad (2)$$

In the case of a partial oxidation reaction, we have an exothermic reaction and it looks as follows:

$$CH_4 + \tfrac{1}{2} O_2 \rightarrow CO + 2H_2 + \text{heat} \quad (3)$$

Another method, ATR (Auto-Thermal Reforming), is a combination of the aforementioned methods. In this process, carbon monoxide is converted to hydrogen according to equation (2).

2. Operating principle of a hydrogen-powered engine

The operating principle of a hydrogen-powered turbine engine is essentially similar to that of an engine powered by traditional aviation fuel. However, there are several differences. First and already mentioned, hydrogen combustion does not contribute to greenhouse gas emissions. However, nitrogen oxides are still produced, as well as water vapor. A hydrogen-burning engine can perform flight operations with a leaner mixture (air-to-fuel ratio), which contributes to lower NO_x, but also results in reduced power output. The amount of nitrogen oxides produced can be further reduced by changes in engine design and by reducing the cruising altitude by about 2 to 3 km compared to that currently used for standard aviation fuels. Hydrogen also has the advantage of being more flammable, which contributes to lower ignition energy compared to aviation kerosene. On the other hand, hydrogen has a higher flame velocity and this can cause flame blow-out and unstable combustion chamber operation. Due to its low density, hydrogen creates also a more uniform mixture in the combustion chamber. In addition, it is also a safer fuel than kerosene, since in aviation accidents deaths are largely due to flames and harmful fumes, while with hydrogen that does not form a vapor cloud.

For engine operation, hydrogen can also be produced from renewable energy sources, through a water electrolysis reaction represented by equation (4).

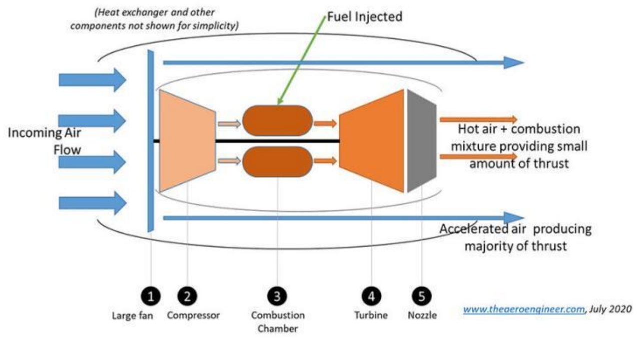

Fig. 3. Schematic of a hydrogen-powered engine [5]

$$H_2O + \text{electricity} \rightarrow H_2 + \tfrac{1}{2}O_2 \quad (4)$$

During alkaline electrolysis, water on the cathode absorbs electrons to form hydrogen. The hydroxide ions move to the anode, where electrons are released. A typical reaction is shown below:

$$\text{Cathode: } 2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$
$$\text{Anode: } 2OH^- \rightarrow \tfrac{1}{2} O_2 + H_2O + 2e^- \quad (5)$$
$$\text{Sum: } H_2O \rightarrow \tfrac{1}{2} O_2 + H_2$$

Fuel cells can also be used to burn hydrogen in aircraft engines, generating energy through a chemical reaction. The best power-to-weight ratio of the system is characterized by PEM (Proton Exchange Membrane) type fuel cells. In PEM cells, water is created on the cathode and heat is released due to the exothermic reaction. Their disadvantage is the cost of materials for their manufacture, such as carbon composites, platinum, and synthetic polymers.

In the case of PEM-type electrolysis, there is a significant improvement in the conductivity due to the use of a solid polymer membrane as an electrolyte. The reactions occurring in PEM are shown by equation (6).

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2$$
$$\text{Anode: } H_2O \rightarrow \tfrac{1}{2} O_2 + H^+ + 2e^- \quad (6)$$
$$\text{Sum: } H_2O \rightarrow \tfrac{1}{2} O_2 + H_2$$

In the case of fuel cells, thermal management is also important. With fuel cell stacks, there is a large accumulation of heat, which can be and impediment for large aircraft.

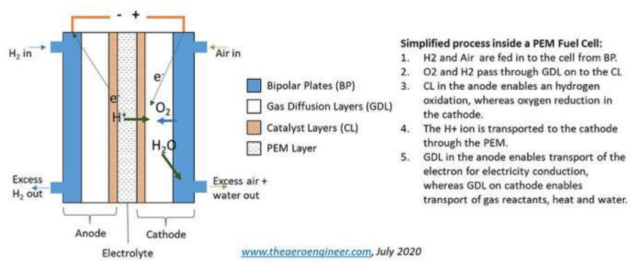

Fig. 4. Fire-fueled PEM [5]

When choosing between the presented methods of using hydrogen in aircraft propulsion, several factors must be taken into account. For long-distance aircraft, hydrogen combustion is more feasible – fuel cells will not yet produce the required energy. For General Aviation, where engines do not require as much power, fuel cells would be more recommended. The literature also suggests that the use of hydrogen combustion can reduce carbon dioxide emissions by 50–75%, while with fuel cells it is as low as 75–90% [11].

In Poland, hydrogen is currently produced from coke oven gas – a thermochemical process. Much better would be producing it by electrolysis, that is, by decomposition of water, under the influence of an electric current, into oxygen and hydrogen – then we are dealing with an electrochemical process. Electricity from hydrogen fuel is obtained through fuel cells during oxidation reactions. In the future, it will also be possible to produce hydrogen by gasifying municipal waste, agricultural waste and biomass. So this would be an additional ecological advantage of this fuel. Figure 5 shows a comparison of the climate impact of synthetic fuel, hydrogen turbines, and hydrogen fuel cells.

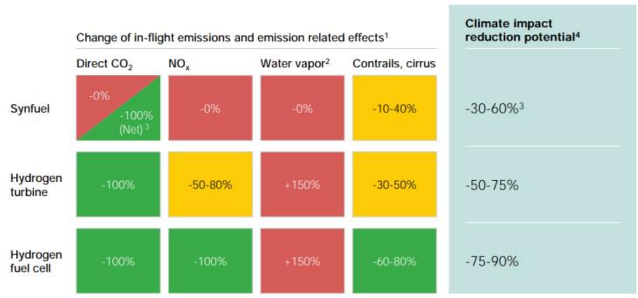

Fig. 5. Comparison of climate impacts between new fuels [11]

3. Distribution and storage

Beneath the surface of this seemingly perfect energy carrier lies a huge challenge: a storage problem. Hydrogen, with its light, gaseous nature, poses unique difficulties when it comes to storage and transportation. Unlike conventional fuels, traditional storage and transportation methods, such as tanks or pipelines, do not work for hydrogen. Instead, hydrogen requires innovative solutions that take into account its special properties and make it a viable energy source.

Hydrogen storage issues are primarily a huge challenge for materials and chemical engineering. The search is on for high-strength materials that, at the same time, do not react with hydrogen or, on the contrary, strong adsorbents that allow to densely accumulate large amounts of hydrogen on their surfaces. The focus is also on elements that form compounds with hydrogen in the form of metal hydrides or complex hydrides. The goal is to concentrate hydrogen elements in the smallest possible volume to achieve the highest volumetric energy density. This can be achieved by: compressing the hydrogen, lowering its temperature and liquefying it, or reducing the intermolecular repulsion force by forming interactions with other materials (metals) [17]. Figure 6 graphically describes the most popular hydrogen storage concepts.

Energy requirements characterize all the previously mentioned forms of increasing hydrogen density. This is an important parameter in evaluating and selecting the best hydrogen storage method. Table 2 summarizes the methods of hydrogen storage, along with information for their initial comparison.

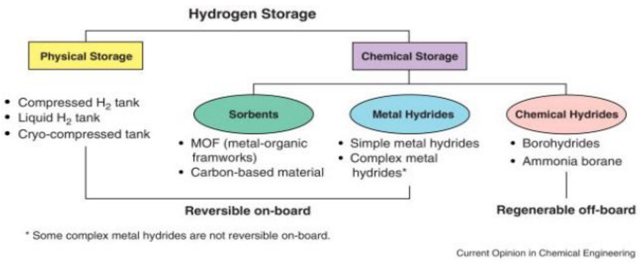

Fig. 6. Ways to store hydrogen [11]

Table 2. The summary of H_2 storage methods with characteristic parameters [26]

Storage method	Volumetric density [kg·m^{-3}]	T [ºC]	P [bar]	Energy consumption [%LHV]
Compressed H_2	< 40	25	800	> 7
Liquid H_2	70.8	–252	1	> 45
Physisorption	20	–80	100	No specific data. Relatively low, depends on the host metal
Metal hydrides	14–156	25	1	No specific data. To provide high stability usually moderate temperatures and pressures are used for hydrogenation.
Complex hydrides	150	> 100	1	No specific data. Requires elevated temperatures for hydrogenation and dehydrogenation

4. Problems and directions of development

As mentioned earlier regarding hydrogen, one of the more difficult issues is how to store it. This gas can be stored in compressed or liquid form and in pressure or cryogenic tanks (hydrogen cooled to –252°C and therefore in a liquid state). Pressure tanks maintain a pressure of 35 to 70 MPa. This requires the use of heavy thick-walled tanks such as steel, which is highly uneconomical for aviation. It is also possible to use composite materials, which would significantly reduce the weight of the tank, unfortunately, compressed hydrogen has almost seven times lower volumetric energy density than aviation kerosene. However, when storing hydrogen in a liquid state, cryogenic tanks that maintain a low temperature are necessary. Limiting heat exchange with the environment with very good results is provided by multilayer tanks with a vacuum space between the layers [1, 2, 8, 14, 16, 18, 22]. Due to the low boiling point of hydrogen, heat exchangers also appear to be necessary in the tank itself to prevent vaporization of the hydrogen and, consequently, an uncontrolled increase in tank pressure. A different method of storing hydrogen is to store it inside the crystallographic lattice of metals and form bonds (ionic or covalent) with the metal elements to form hydrides (Fig. 7) [21]. This method is still being developed so that hydrogenation and dehydrogenation of metals can take place under the most applicable conditions (temperatures and pressures close to ambient) [24]. For the time being, however, they are not the best solution for aviation due to their weight. Their application will most likely be limited to large-scale ground storage and transportation. Due to their large surface area and thermal stability, carbon nanotubes are also being considered for hydrogen storage. The large surface area of nanotubes makes them, along with porous materials, appear to be ideal adsorbents for hydrogen storage on their surface based on van der Waals forces. The forces of these bonds, however, are so small that they play a significant role at reduced temperatures of the order of 200 K. Because of their mass and greater potential for hydrogen storage (including the potential for rapid refueling), they represent a promising hydrogen storage method for the aerospace sector [6, 19]. Worth noting are complex metal hydrides of such metals as Lithium, Manganese, Beryllium, and Al. Compared to their simpler counterparts, they often have twice the ratio of hydrogen atoms to metal atoms. The relatively high % hydrogen content by weight of the whole compound is their great advantage [12].

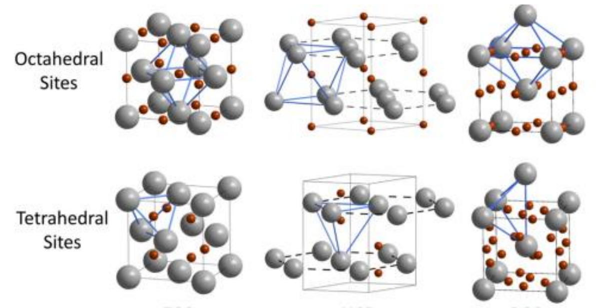

Fig. 7. Hydrogen occupies octahedral or tetrahedral sites in interstitial hydrides. Interstitial sites are marked by brown dots [13]; FCC – face centered cubic, HCP – hexagonal close-packed, BCC – body-centered cubic

Currently, airports do not have infrastructure designed for hydrogen distribution, so this will involve upgrading them. This is an extremely costly challenge, as it requires financial outlays not only for the infrastructure but also for personnel training, legal safeguards or matters related to meeting safety standards. For the moment, however, it is impossible to say that hydrogen is a 100% green solution. The process of production and storage would consume a great deal of energy. Studies also point to problems with fuel pumps and heat exchangers, making it necessary for the engine to be redesigned. In addition, the fuel tanks in the aircraft require a larger volume than the tanks for typical Jet A-1 fuel. Due to the problem of balancing the aircraft, it is suggested that the tanks be located behind the passenger cabin. However, the aircraft's center of gravity would then change. Thus, a second solution could be to place two tanks – one in front of and the other behind the cabin, or to use the space above the passenger cabin for this purpose. An example of liquid hydrogen tank placement is presented in Fig. 8.

Much more of a problem than storing hydrogen can be leaks. Due to the fact that it is a very light gas that can burn explosively by forming a mixture with air. It, therefore requires additional safeguards. Hydrogen also causes an increase in the brittleness of metal materials, which generates damage to fuel tanks and fuel system components.

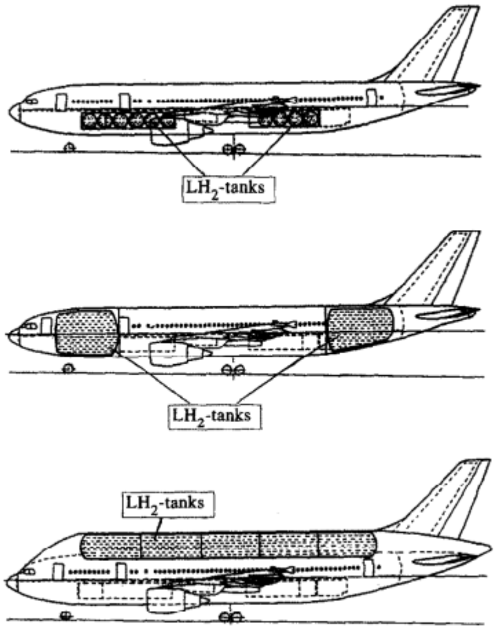

Fig. 8. Conceptual layout of fuel tanks in an aircraft [3]

5. Economic aspect

The cost of traveling on a hydrogen-powered plane will be dictated by the cost of the fuel. The price of an airline ticket includes the cost of producing the fuel but also charges for the pollutants emitted. For the moment, Jet-A fuel is much cheaper than "green solutions". Hydrogen will become profitable for airlines when there is an increase in fees for the emitted carbon footprint for traditional aviation fuels. Fuel costs depending on "carbon compensation" over the years in the European Union and the United States are presented in Fig. 9.

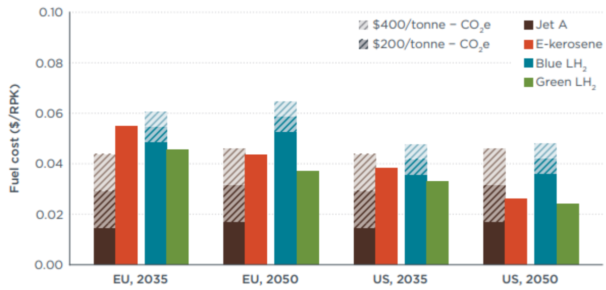

Fig. 9. Comparison of jet fuel costs [15]

The cost of aviation kerosene and "blue" hydrogen is expected to increase over the years. In contrast, the costs of synthetic fuel (E-kerosene) and "green" hydrogen will decrease. The projections are indicative of the emphasis being placed on low emissions. Hydrogen is certainly one of the fuels of the future, as it can provide much more energy than standard aviation kerosene, which would enable high-speed flights, while not contributing to carbon emissions. However, hydrogen is not a 100% environmentally friendly solution due to the condensation plumes produced during combustion, leading to climate warming in large quantities. Nevertheless, it is one of the greenest options for powering aircraft engines. A comparison of the amount of carbon dioxide produced by aviation fuels is presented in Fig. 10.

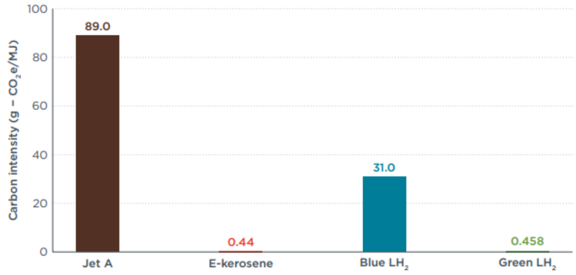

Fig. 10. Comparison of the amount of carbon dioxide produced for different aviation fuels [15]

It can be seen that among the fuel types presented, kerosene and blue hydrogen are responsible for the largest amount of generated CO_2 is accounted for by aviation kerosene and blue hydrogen. A low carbon footprint can be achieved by using synthetic fuel produced from 100% renewable sources or green hydrogen. The predictions shown in Fig. 9 represent the best-case scenario for carbon dioxide production depending on the fuel chosen, but the differences between kerosene and hydrogen are significant enough to recognize the validity of using hydrogen in air transport.

6. Internal combustion engine powered by hydrogen

When assessing the value of hydrogen as a fuel of the future, it is worth paying attention to the industry. An example from the industry can be found in the research of an automotive company that has been going on for nearly a decade. The Japanese manufacturer saw the potential in hydrogen fuel as early as 2014 and developed the technology over the following years. In addition to hydrogen cells, the use of which we can observe today by following one of the corporation's cars, a large amount of effort was put into a hydrogen-powered piston engine. Initially, hydrogen combustion was used in hydrogen-gasoline mixtures. As demonstrated by Karagöz et al. [7], among others, this is not the most efficient, as it contributes to an increase in brake specific fuel consumption (BSFC) (Fig. 11). This is due to a number of factors including: a much higher flame rate, a difference in the mixture equivalence ratio, and a much lower energy required to ignite the hydrogen resulting in a tendency for knocking combustion to occur. This problem was comprehensively overviewed by the Matla [10] indicating the compression ratio and mixture equivalence ratio influence on the knocking combustion and discussing advantages of prechamber implementation as a method of combustion control feature.

This comes to a consequent reduction in engine power of up to 25% for 50% hydrogen content in the mixture. In subsequent steps, further successes were recorded with pure hydrogen fuel stored in a high-pressure tank and then with a liquid hydrogen tank and an intermediate hydrogen gas tank. Research conducted by Longwic et al. [9] indicates however, that diesel fuel/H_2 blends have a significantly beneficial impact on the mean effective pressure. Moreover authors state that in the case of specific diesel engine 62% of carbon dioxide emission reduction was observed (for 46% of hydrogen in the blend) alongside with nearly 76% of soot reduction.

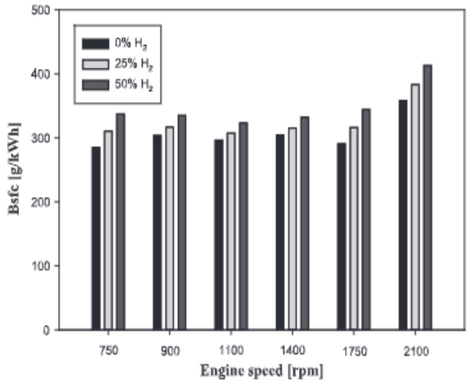

Fig. 11. Piston engine BSFC at range of different rpm for different hydrogen content in a mixture [7]

7. Conclusions

The analysis, done as a part of the research and presented in the article, provides expertise on the directions of aviation development regarding hydrogen propulsion. It needs to overcome economic and ecological difficulties but also address the demand for flights at high speeds (e.g., X-43 A). Authors conduct research on the toxicity of exhaust gases of aircraft propulsion and the possibility of using hydrogen in this type of propulsion systems. The conclusions drawn from the analyses are as follows:

Hydrogen will not fully eliminate nitrogen oxides emissions, yet it will eliminate carbon oxides emission. It is also the main competitor for batteries as a mobile clean energy carrier. The real future of hydrogen depends on efforts to overcome infrastructure limitations and unfavorable chemical properties. The most important issues in hydrogen utilization research at this point are weight issues – tanks must be developed that will reduce the weight by at least half compared to currently proposed solutions and, as always, safety issues.

Storing hydrogen in the solid state is very promising and provides a high volumetric density of hydrogen, higher than that of compressed and liquid hydrogen. However, the energy required to recover hydrogen from the structure of the compound (available at temperatures on the order of 360–500 K) limits the application of this method to above-ground hydrogen storage or large-scale transport. An exception is the storage of hydrogen on the surface of metals based on physical adsorption, but this method appears to be inferior in terms of efficiency compared to liquid hydrogen. The ongoing work and decisions made by the world's largest companies lead to believe that hydrogen has a future in aviation, and it belongs to liquid hydrogen. In favor of hydrogen is the calorific value of this fuel, although due to its low density, the tanks will have to be larger, the mass of hydrogen required for the mission will be almost three times lower than the mass of aviation kerosene while maintaining combustion efficiency.

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