Liquefied and chemical hydrogen storage in contemporary small drones’ fuel cell propulsion systems

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Abstract. Contemporary manufactured small Unmanned Aerial Vehicles (UAVs, drones) use mostly electric engines for their drive. Application of such propulsion systems need elaborating of efficient and light electric energy sources. There are used at present mainly two methods of on-board energy storing. First is usage of possibly efficient batteries. The second method is production of electric energy on-board with use of fuel cells (FC). That way requires the pure hydrogen fuel to be supplied to FC. Hydrogen can be stored in compressed state in pressure bottles or in liquid state in cryogenic tanks. The other much safer way of hydrogen storage is use of the chemical compounds containing that element. This article relates only to liquid and chemical hydrogen storage systems being in experimental phase yet. The results of researches in this field can determine the direction of further development. The chosen examples of experimental liquid hydrogen storage for the needs of small drones’ fuelling have been presented in article.

1. Introduction
Small UAVs (fixed-wings and multi-copters aircraft) are driven mostly by electric engines because of their low weight and easiness of control as well as possibility for elimination of thermal and sound trace [1]. The electric engines are more efficient and reliable than combustion engines but if we take into account efficiency of the overall system, the value of efficiency is comparable. Equipment required for electric propulsion increase the whole system weight limiting the flight time. The issue of extending the endurance of small drones is now the most important task for aviation R&D centres from that area. Development of the efficient batteries and application of modern fuel cells (FC) is one of the ways to achieve the much longer flights.

High purity hydrogen which is the “fuel” for FC should be taken on-board of UAV. The main issue within that area at present is the improvement of technology of hydrogen storage. Methods of liquefied and chemical hydrogen storage and on-board production on the base of examples of constructions of UAVs’ propulsion systems are presented below and listed according to UAVs manufacturer’s names and particular technical solutions.

It seems that the more proper expression would be "liquefied hydrogen" instead of "liquid hydrogen" but the author retains the most popular term used commonly in literature.

2. Liquid hydrogen storage

2.1. U.S. Naval Research Laboratory NRL – Ion Tiger UAV, liquid hydrogen fuel cell version
U.S. Naval Research Laboratory (NRL) has been leading research on liquid hydrogen fuelling of drones parallel to compressed gas feeding. Special version (figure 1) of described above the Ion Tiger
UAV fed with liquid hydrogen was tested in 2013 [1]. Hydrogen stored in a lightweight cryogenic tank (figure 2) together with Protonex’s 550W fuel cell enabled Ion Tiger to fly for 48-hours and 1 minute on April 2013. Density of liquid hydrogen (LH$_2$) is three times more than compressed one allowing increase of flight endurance. The Ion Tiger would be able to fly for 4 hours (only) on the comparable weight Li-Po batteries [1], [2].

![Figure 1. Liquid hydrogen fuel cell powered Ion Tiger UAV in flight [3].](image1)

![Figure 2. Cryogenic hydrogen tank developed by NRL and mounted in the LH$_2$ version of Ion Tiger UAV [5].](image2)

2.2. Hylium Industries Inc. — liquid hydrogen fuel cell system

South Korea’s company Hylium Industries Inc. is a manufacturer of cryogenic equipment for helium and hydrogen storage in liquid phase established in 2014 [6]. Research are continued to become South Korea independent of import of low temperature technologies especially in military area. The present proposal of Hylium Industries is related to small UAV’s propulsion. It is a LH$_2$ fuel cell system mounted in a 6-propeller multicopter (figure 3) destined generally for civil applications. According to company’s information the cryogenic LH$_2$ vessel presented in figure 4 has been used as fuel tank of that UAV.

![Figure 3. Hylium Industries’s LH$_2$ powered UAV [7].](image3)

![Figure 4. Hylium Industries’s cryogenic LH$_2$ bottle for UAV [8].](image4)

Hylium Industries company manufactures also an equipment for hydrogen liquefying however it is not useful for field refuelling of H$_2$ cryogenic tanks. At present the manufacturer offers a "portable" LH$_2$ refuelling set presented in figure 5.

![Figure 5. Hylium Industries’s portable LH$_2$ refuelling set for UAV [9].](image5)
3. Chemical hydrogen storage

A chemical hydride can store hydrogen at low pressure with relatively high density of packing. Hydrogen can be released along with the demand by the fuel cell. Such systems work at low pressures without heavy tanks of compressed hydrogen. There are several ways of chemical hydrogen fuel storage on-board the UAVs being tested intensively by different R&D centres related to drones’ industry. The most advanced researches are connected with sodium borohydride (NaBH₄), ammonia borane (NH₃BH₃) and liquid hydrocarbons such as methane, propane, methanol or formic acid (CH₂O₂). Examples of results of research within that area are presented below.

3.1. Sodium borohydride

3.1.1. Department of Aerospace Engineering, College of Engineering, Chosun University, South Korea — NaBH₄ hydrogen generator with volume-exchange fuel tank. Interesting design of a H₂ fuel supply system incorporating fuel cell and the sodium borohydride (NaBH₄) hydrogen generator was presented in 2014 [10]. The water solution of NaBH₄ containing about 11% of hydrogen was a hydrogen source for FC stored in a fuel tank. The equation: NaBH₄ + 2H₂O → NaBO₂ + 4H₂ was a base for obtaining the H₂ during the hydrolysis. Initiation of that process takes place at room temperature without need of heating from external source.

Figure 6. Scheme of fuel supply system using NaBH₄ hydrogen generator [10].

Figure 7. Principle of sodium borohydride (NaBH₄) flow in hydrogen generator with volume-exchange fuel tank [10].
The H₂ fuelling system consisted of hydrogen generator, volume-exchange fuel tank, pump of NaBH₄ water-solution, catalytic reactor and Horizon Proton Exchange Membrane Fuel Cell (PEMFC) stack H-100 (100 W). There was developed a single volume-exchange fuel tank contained fuel and liquid NaBO₂ (as by-product) separated by rubber bag inserted in the fuel tank. The NaBO₂ was recycled to NaBH₄ by absorbing hydrogen. The catalytic reactor consisted of a Co-B (cobalt) catalyst applied on a porous ceramic material. Obtained voltage was 12.0 V and the power output was slightly more than 100 W. The scheme of H₂ fuel supply system with volume-exchange fuel tank is presented in figure 6. The principle of NaBH₄ flow in hydrogen generator with volume-exchange fuel tank is shown in figure 7 [10].

3.1.2. Marmara Research Centre Energy Institute and National Boron Research Institute — Hydrogen Generator system with Co-B catalyst and FC system. The similar to presented above hydrogen generation system for propulsion of a small home-designed UAV utilizing 20% NaBH₄ solution and a 200 W fuel cell system were developed by Marmara Research Centre Energy Institute and National Boron Research Institute (Turkey). A light weight (0.6 kg) hydrogen generation system using also as in mentioned above example a cobalt-base Co-B catalyst was delivering about 5 dm³/min of hydrogen. A FC system of mass 1.6 kg was generating more than 200 W at about 24 V. An experimental UAV equipped with hydrogen generator and FC stack had wingspan of 2.5 m and total weight 7.5 kg. The drone built from carbon fibre and composite materials is presented in figure 8. The fuel cell stack consisted of 50 cells used for powering is presented in figure 9.

Figure 8. Experimental UAV fitted with hydrogen generator working on 20% water solution of NaBH₄ and FC system developed by Marmara Research Centre Energy Institute and National Boron Research Institute (Turkey) [11].

Figure 9. Hydrogen Fuel Cell system for NaBH₄ driven UAV [11].

3.1.3. BALLARD — Sodium borohydride cartridges (one time use). One of the ways to store hydrogen for small UAVs is application of one time use chemical hydride cartridges. The idea of such solution has been already presented in other author’s article at the case of H3 Dynamics’s AEROPAK-L using a hydrogen-rich liquid chemical cartridge with combination of PEM fuel cell. Hydrogen can be released on-demand as the fuel cell requires it. Ballard-Protonex company elaborated such system which is load-depending and can achieve full hydrogen output in 3-5 seconds from the start-up and stop hydrogen production immediately when there is no demand. The hydride cartridge presented in figure 10 can be installed before flight and work with the fuel cell to generate energy for electric engine driven propeller. The utilized cartridges
can be discarded or returned for refuelling.

![Figure 10. Ballard-Protonex’s NaBH₄ one time use cartridges 1350 Wh [12].](image)

3.2. Korea Institute of Science and Technology — Ammonia borane (NH₃BH₃)

Ammonia borane (NH₃BH₃) is a chemical way of hydrogen storage similar to discussed above. The hydrogen storage capacity in this case can reach 19.6%.

The hydrogen generator working according to this principle was applied by the Fuel Cell Research Centre at the Korea Institute of Science and Technology to power a small electric motor driven UAV in 2013 [13]. The process of hydrogen release took place in 85–145 °C according to the following equation: NH₃ + BH₃ / NH₂BH₂ + H₂. Ammonia borane released hydrogen (dehydrogenation process during heating) but unfortunately also by-products in the form of gaseous impurities containing borazine and ammonia. According to researchers’ report Hydrogen generator showed the rapid H₂ release rate up to 3.3 dm³(H₂) min⁻¹ with fast load-following capability. That fast response to load change was essential for correct work of the whole feeding system. The experimental RemoEye-006 UAV of 2.7 m wingspan and 1.7 m length manufactured by Uconsystem Corp. (South Korea) equipped with mentioned system and 200W PEMFC demonstrated relatively long flight (57 min). The silhouette of current RemoEye-006 UAV has been presented in figure 11.

![Figure 11. RemoEye-006 UAV manufactured by Uconsystem Corp. [14].](image)

3.3. Cella Energy and the University College London — Ammonia borane (NH₃BH₃)

The very innovative design of ammonia borane (NH₃BH₃) application to UAV propulsion was demonstrated in 2016 by Cella Energy and the University College London in collaboration with the Scottish Association for Marine Science and Arcola Energy. Cella used own elaborated and manufactured solid pellets contained NH₂BH₃ with 12 % H₂. That way enabled safety hydrogen storage in the unpressurized cartridge at room temperature. The plastic-like pellets were made of a proprietary chemical compound incorporating a polyethylene oxide polyether as shown in figure 13. According to Cella information one gram of the pellets can release up to 1 dm³ of H₂ when heated to 100-120°C in about 3 min after start-up. The Cella pellets were stored in the wings. The scheme of hydrogen pellets arrangement in a drone’ wing is presented in figure 12.
The flight test of the experimental Raptor E1 electric drone (figure 14) fitted with hydrogen pellets was performed in January 2016 at Oban Airport in Scotland [15], [16].

4. Liquid hydrocarbons storage

4.1. INHA University (South Korea) — Direct Methanol Fuel Cell (DMFC)

The example of application of a DMFC for UAV propulsion can be the works of INHA University (South Korea) Eco-Smart Power Lab team in 2013 [20]. Developed 200W DMFC system was mounted together with Li-Po auxiliary battery system in an 11 kg UAV with a wingspan of 2.64 m and total length of 1.65 m. A usual battery aided take-off phase was applied what enabled successful flights with methanol tank volume 1.62 dm³. The tested drone with elaborated by INHA DMFC is shown in figure 15.

Figure 12. Scheme of Cella’s pellets construction inside a drone wing [18].

The flight test of the experimental Raptor E1 electric drone (figure 14) fitted with hydrogen pellets was performed in January 2016 at Oban Airport in Scotland [15], [16].

Figure 13. Cella’s solid pellets contained NH₃BH₃ with 12% H₂ [17].

Figure 14. Flight of experimental Raptor E1 equipped with Cella’s hydrogen pellets stored in the wings [19], [15].

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4.2. Silent Falcon UAS Technologies — Formic acid (CH$_2$O$_2$) Proton Exchange Membrane Fuel Cell

The similar process to DMFC takes place in a formic acid (CH$_2$O$_2$) Fuel Cell. Formic acid releases H$_2$ according to the equation: CH$_2$O$_2$/ H$_2$ + CO$_2$. The hydrogen content in formic acid is about 4.4 % and its decomposition (dehydrogenation) takes place at ambient temperature what makes that process should begin immediately after start-up of the whole system.

Application of such formic acid reformer-based fuel cell technology was announced by Silent Falcon UAS Technologies cooperating with Neah Power Systems Inc. in 2014 [21]. That solution was to be used in the Silent Falcon UAV shown in figure 16 which was in basic version a solar-photovoltaic drone. Basic specifications of Silent Falcon UAV are – 4.4 m wingspan, 1.9 m length, 14.5 kg weight and 75–6000 m operating altitude. There is no however reliable information yet about results of these researches.

4.3. Lockheed Martin and DARPA — Methane or propane Solid Oxide Fuel Cell (SOFC)

Application of a SOFC enables to drive the drone with conventional hydrocarbon fuels. Tests of that kind of propulsion have been carrying out for more than 10 years. One of early probes was conducted with Stalker XE UAV (Stalker eXtended Endurance UAV) in 2011-2013 shown in figure 17. The Stalker XE described by author in 2015 [1] was driven by a SOFC that used LPG or propane as a fuel. This construction provided enough energy to fly more than 8 hours what was three times more than basic Stalker version.
The Stalker XE energy feeding system consisted of mentioned propane SOFC and a small conventional Li-Po battery to support power peaks. The FC technology was developed by Lockheed Martin in collaboration with Defence Advanced Research Projects Agency (DARPA) and Ultra Electronics Holdings. Stalker XE UAV basic specifications are shown in the table 1.

Table 1. Stalker XE UAV basic specifications [23], [24].

| Parameter                  | Data                     |
|----------------------------|--------------------------|
| Wingspan                   | 3.6 m                    |
| Altitude                   | Up to 4600 m             |
| MTOW                       | 10 kg                    |
| Maximum speed              | 72 km/h                  |
| Energy supply system       | LPG or propane fuelled SOFC |
| Engine                     | Electric                 |
| Endurance                  | 8 h (2011), 13 h (2013)   |

The fuel cell efficiency was about 18.8 % and start-up time about 20 min because of the high operational temperature. The initial endurance of 8 h was improved later to nearly 13 h in 2013.

5. FC-based hybrid drones’ propulsion
There are several present concepts of UAV propulsion with use of hybrid power-plants in aim of gain longer endurance. These concepts are probably of temporary character before the high efficiency and lightweight power sources are developed. The examples of such solutions have been presented below.

5.1. National Aeronautics and Space Agency (NASA) — Helios HALE UAV
The NASA programme carried out with AeroVironment Inc. in years 1981–2001 was one of pioneering projects of solar-hydrogen drones. As a result of previous research the huge 75 m wingspan solar-hydrogen driven High Altitude Long Endurance (HALE) UAV was built. That drone named Helios used the hydrogen PEM fuel cell technique based on water hydrolysis system providing the energy supply for night flight phase when solar modules were not working [1]. The view of Helios in flight is shown in the figure 18. Lightweight and flexible photovoltaic cells were provided by well-known in this area firm Alta Devices. Helios HALE UAV performed high-altitude flight in the summer of 2001 reaching 29500 m and setting the world records in flight endurance and altitude [25]. The conception of its propulsion is valid also today and is applied in some current constructions however, with difficulty because of small dimensions of described drones.

5.2. US Navy Research Laboratory (NRL) — Hybrid Tiger UAV
US Navy Research Laboratory (NRL) has been testing a prototype of new version of described above Ion Tiger UAV called Hybrid Tiger is presented in figure 19. This drone which is the successor of Ion Tiger described above, but this time has been using a combination of hydrogen fuel cell with solar photovoltaic panels mounted on the upper surface of the wings. The control system is fitted with
autonomous energy preserving algorithms including thermal updrafts usage to achieve the assumed long endurance more than three days. Hybrid Tiger’s first experimental flight is expected to take place this year (2018).

6. Conclusions
The hydrogen fuel cells application for drones’ propulsion is one of the directions of contemporary research works. Achieving a high efficiency of propulsion and hence the long UAVs’ endurance requires application of the advanced methods of hydrogen storage and then efficient energy conversion to electric current. Conception of hydrogen storage in liquid state or in chemical compounds on-board of UAV is still difficult to apply because of many technical issues. Presented above results of researches are mainly of experimental character but indicate one of the probable future development in this field. The idea of hybrid propulsion systems of drones combining hydrogen fuel cells with solar photovoltaic technology or combustion engines is not new, but returns in the up-to-date state of technique. The great development of all related scientific and technical disciplines will certainly affect conditions of our life independently from the success of the researches.

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Figure 19. NRL’s Hybrid Tiger UAV driven with H₂ FC and photovoltaic panels [27].
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