

Issues related to fuel cells application to small drones propulsion

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Abstract. Application of different energy sources for electric engines used to drive small propeller drones with particular attention paid to Fuel Cells (FC) types has been discussed in this article. Short review of principles of work of chosen types of fuel cells as well as their performance dependent on the kind of chosen energy storing and supply method has been discussed. Requirements of FC drive of Unmanned Aerial Vehicles (UAVs) regarding to the hydrogen generating, storing and possibilities of fast refuelling have been presented. The example of contemporary solution of hydrogen FC system using compressed hydrogen storage which is common to many experimental and commercial small drones has been given.

1. Introduction

The interest of contemporary aerial industry has turned towards the Unmanned Aerial Vehicles (UAVs). That trend is visible not only within military applications but also in the field of commercial civil aviation. For commercial use, drones have to provide much more extended flight time. A longer flight times as well as quick refuelling are the most desirable features enabling the wide range of possibilities of UAVs' application. Drones may be used, among the others for search and rescue, aerial photography, fire protection, inspection of difficult to access areas, agriculture, police intelligence and others, hence a huge increase in interest of these vehicles are visible. The drones' commercial market is expected to growth over the next few years, from 250000 working drones in 2017 to more than 2500000 working drones by 2021.

Independently of combustion engines (piston, turbojet, turboshaft) applied mainly to big and medium size drones such as: MQ-1 Predator, Aerostar TUAS, MQ-9 Reaper, Global Hawk, Camcopter S-100, MQ-08 Fire-Scout or K-MAX UAS [1, 2], the electric engines or hybrid gasoline-electric propulsion (i.e. Eagle Hero VTOL) are used in mini-drones (Maximum Take-Off Weight below 25 kg).

Electric propulsion of mini UAVs makes potentially a possibility for lower cost, elimination of thermal signature, reduction of sound trace and lack of exhaust gases [4]. Contemporary lithium-polymer batteries give limited specific energy rates, enabling a limited endurance of less than 60 min. Hence, the combinations of batteries and Fuel Cells (FC) in hybrid propulsion systems are tried to be applied.

The non-commercial drones are driven usually by electric engines fed by use of battery storage, however there are more and more often used micro-jet and micro-turbine engines (by air modellers mainly). It seems the military has been watching carefully that area for many years what effects in serious research works on micro-turbine propulsion carried out nowadays by big military aviation firms [5]. These kinds of propulsion are not satisfying considering the flight time and endurance of small UAVs.

The efficiency of the propulsion system depends on its type. A battery system has more than 70% efficiency, a fuel-cell – about 45% and combustion engine – about 40%. The conclusion is to use only



battery propulsion and that is the reason why more than 95% of present commercial UAVs use batteries as a power source, usually Lithium-Polymer (Li-Po) and Lithium-Ion (Li-Ion). However, an energy source as well as propulsion type making a flight performance is depended on the whole system. Hence, addition of batteries to the system does not increase the flight time and payload capability. The only way is to increase the energy storing quality. The mass-specific energy (Wh/kg) and volumetric specific energy (Wh/dm³) of batteries have to become bigger.

The choice for an energy source is depended on drone's purpose and mission, i.e. to carry big payloads or fly long distances (LE – Long Endurance), low, medium or high altitudes (LA, MA or HA) or realize combined tasks (LALE, MALE, HALE).

2. Mass specific energy of different UAVs' propulsion systems

The graph of energy density of different sources is shown in figure 1. The best values of mass specific energy are presented by liquid or highly compressed hydrogen. These values are much better than for liquid hydrocarbon fuels like kerosene, gasoline, LPG or LNG. Going forward it can be stated that among the different electric energy storage methods fuel cells are also the best solution. The graph showing specific energy (electric) of different storage technologies including fuel cells is presented in figure 2.

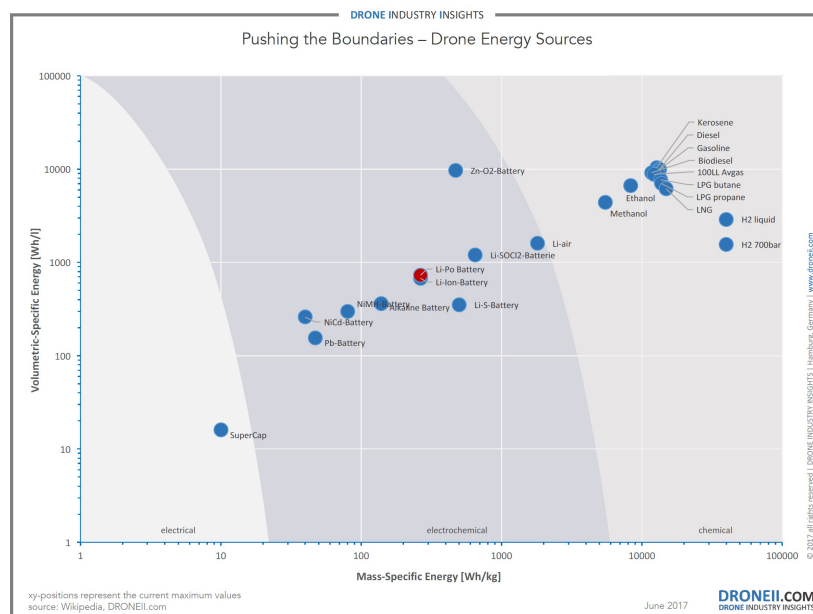


Figure 1. Energy density of different sources [6].

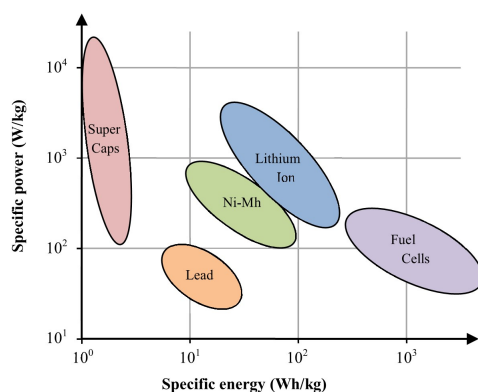


Figure 2. Specific energy and specific power of different storage technologies [7].

As stated above, fuel cells are a power source with significantly higher energy density than the best lithium-ion batteries typically used in drones' propulsion. That is the reason why big attention is paid to such kind of energy storage, not only in the automotive industry but also in the field of military and commercial aviation.

The direction of development of contemporary UAV's propulsion is use of hybrid systems consisted of batteries and fuel cells. Usually that is a good combination of high energy density batteries and hydrogen fuel cells. Hydrogen fuel may be stored on board in pressure bottles or chemical compounds. There is also another, much more complicated system, where hydrogen is produced on board in an electrolyser using the electric energy from photo-voltaic cells [4] making the closed fuel system. That solution is still in an experimental stage.

The most frequently used energy sources for drones are Li-Po and Li-Ion batteries. Probably in close future better kinds of batteries with higher energy density will be available. There are conducted intensive research works on Lithium-Thionyl-Chloride batteries (Li-SOCl_2) which have 2 times higher mass-specific energy than Li-Po ones. They all are very expensive yet, but together with the development of their technology, they will be more available. One can give an example of Lithium-Air (Li-air) or Lithium-Sulphur-batteries (Li-S) expected to have even 7–10 times higher energy density.

The basic information on types of fuel cells and their possibilities to application to drones' propulsion in the current state of the art is presented below.

3. Types of fuel cells

Electricity is usually produced in fuel cells from hydrogen and oxygen in an electrochemical reaction. The reaction is exothermic and its side effect is water. In a fuel cell, chemical energy is converted into electrical energy directly. Conventional electricity generation consists of a three-stage energy conversion process: chemical – thermal, thermal – mechanical and mechanical – electricity.

Many fuel cells types which do not require hydrogen as fuel are interesting but they are not possible to use in drones' propulsion systems on present stage of knowledge. One can divide fuel cells taking under account i.e. type of electrolyte, work temperature, electric efficiency and other. There are also in several cases problems with products of fuel cell electro-chemical reaction (CO , sulphides, halides) treated as contamination.

In a case of mobile applications the main fuel cell type is the Proton Exchange Membrane (PEM), named also Polymer Electrolyte Membrane Fuel Cell (PEMFC) working with pure hydrogen. That kind of fuel cell has the best properties in terms of use in drones, however several other types of fuel cells are also intensively investigated by UAV manufacturers. Generally are used PFSA (PerFluoroSulfonic Acid) membranes of trade name Nafion, produced by DuPont.

PEMs are the most suitable ones due to their high flexibility. The advantageous features of PEM fuel cells from the point of view of transport applications are among the others: high power density, fast start-up time, high efficiency, low operating temperature, and easy and safe handling.

The chosen examples of kinds of fuel cells and their properties are presented in table 1.

Table 1. Comparison of chosen fuel cell types [8].

Fuel cell type	Typical electrolyte	Typical fuel	Major contaminants	Operation temperature ($^{\circ}\text{C}$)	Electrical efficiency (%)	Charge carrier
Low-temperature PEM	Solid Nafion Solid composite Nafion	Hydrogen	CO , H_2S	60 – 80	40 – 60	H^+
High-temperature PEM	Polybenzimidazole (PBI) doped in phosphoric acid	Hydrogen	CO	110 – 180	50 – 60	H^+
Solid Oxide	Solid yttrium-stabilized zirconia (YSZ)	Hydrocarbons (methane, propane)	Sulphides	800 – 1000	55 – 65	O^{2-}
Molten carbonate	Liquid alkali carbonate (Li_2CO_3 , Na_2CO_3 , K_2CO_3) in lithium aluminate (LiAlO_2)	Methane	Sulphides Halides	600 – 700	55 – 65	CO_3^{2-}
Phosphoric Acid	Concentrated liquid	Hydrogen	CO , H_2S ,	160 – 220	36 – 45	H^+

	phosphoric acid (H_3PO_4) in silicon carbide (SiC)		Siloxane			
Alkaline	Water solution of potassium hydroxide (KOH) Anion exchange membrane (AEM)	Hydrogen	CO_2	Below zero – 230	60 – 70	H^-
Direct methanol	Solid Nafion	Liquid methanol- water solution	CO	Ambient – 110	35 – 60	H^+
Direct carbon	Solid yttrium-stabilized zirconia (YSZ) Molten carbonate Molten hydroxide	Solid carbon (e.g., coal, coke, biomass)	CO_2 , Ash, Sulphur	600 – 1000	70 – 90	O^{2-}
Direct borohydride	Solid Nafion Anion exchange membrane (AEM)	Sodium borohydride (NaBH_4)	—	20 – 85	40 – 50	Na^+

Analysing the different kinds of fuel cells one can state that the potential possibility of their application to UAVs' propulsion depends on the level of technological maturity and balance of advantages and disadvantages. From among the presented FCs the most matured ones are: Low Temperature PEM (LTPEM), Solid Oxide FC (SOFC), Molten Carbonate FC (MCFC) and Direct Methanol FC (DMFC). One of the most promising is Alkaline FC (AFC), but still the use of that FC type is limited to special applications like NASA space programme.

In the case of Solid Oxide FC, the kind of fuel (hydrocarbons) makes it very flexible. In spite of high work temperature several tests of that energy source for drone's propulsion have been done yet [4]. The possibility of use of hydrocarbon fuel is very attractive, but is still very difficult in realization.

Direct carbon FC presents the higher electrical efficiency 70–90 % but it is nowadays the energy source for stationary applications only.

The other factors of potential use of FCs to drones propulsion are the overall costs of FC system components (mainly catalysts), power density and tolerance to fuel contaminants. Very important, particularly in military applications, is as fast as possible start-up and dynamic response to energy demand. Here the best performance presents LTPEM due to low temperature operation.

Particular attention should be paid to three types of fuel cells, which are being nowadays applied or tested as drones' energy supply: PEMFC, SOFC and DMFC.

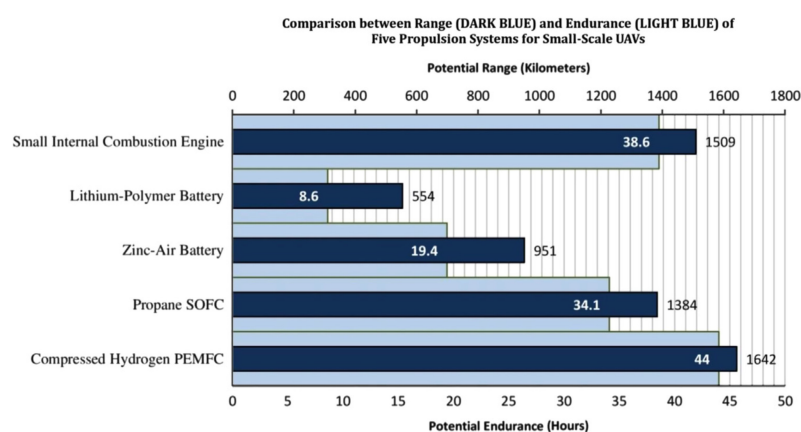


Figure 3. Comparison between different proposed UAV small-scale propulsion systems [8].

Fuel cells' quiet operation and low heat dissipation (low acoustic and heat trace) is the very desirable feature making that source of UAVs' propulsion advantageous over internal combustion engines and well fitted to UAVs' stealth nature.

Propulsion systems are relatively complicated and consist of fuel tanks or fuel generators, fuel cells, buffer batteries and electronic control equipment providing proper battery charging and optimal energy utilization for maximum efficiency of propellers' electric engines and flight endurance of UAVs.

On present level of technological state the absence of buffer batteries seems to be impossible because of the safety reasons. Here it should be mentioned mainly Li-Po and Zinc-Air or Li-Air (still experimental) batteries.

A comparison among five different UAV propulsion systems presented in figure 3 shows that a PEMFC propulsion system with compressed hydrogen has the highest potential for endurance and range.

4. Principles of work of fuel cells

Fuel cells produce electricity directly from the chemical energy of the fuel with use of electrochemical reaction. Efficiency of such conversion is greater or similar to the most efficient combustion engines. The operating voltage and current depend on the number of cells in a stack and the maximum current is determined by the cross-sectional area of each cell defining the ability of power storage in the fuel cell stack. Proper operation of fuel stack requires auxiliary equipment, so called 'balance-of-plant' and that equipment makes structure more complicated and heavier.

Fuel cell name comes from the source of hydrogen (as the fuel) and from the type of the electrolyte it use. Fuel cell uses chemical energy from external supply of hydrogen and oxygen taken usually from ambient air. There is no combustion inside FC - oxidation of the hydrogen occurs electrochemically when hydrogen atoms react with oxygen atoms forming water. During this process, released electrons flowing through an external circuit make electric current. Fuel cells size can be both miniature producing several watts and large, producing megawatts (in power plants). All fuel cells consist of two electrodes separated by a solid or liquid electrolyte which carries electrically charged particles. To speed up the reactions at the electrodes a catalyst is often used. Fuel cell name comes from the source of hydrogen (as the fuel) and from the type of the electrolyte they use.

The schemes and short characteristics of chosen kinds of fuel cells are presented below in figures 4–6.

4.1. Proton Exchange Membrane Fuel Cell – PEMFC

Physicochemical characteristics:

- Electrolyte: water-based, acidic polymer membrane (polymer electrolyte membrane FC),
- Also called polymer electrolyte membrane fuel cells,
- Catalyst: platinum-based on both electrodes,
- Fuel: generally hydrogen,
- Operation temperature range - relatively low (below 100°C), high temperature versions use a mineral acid-based electrolyte and operate up to 200°C,
- Electrical output: varied.

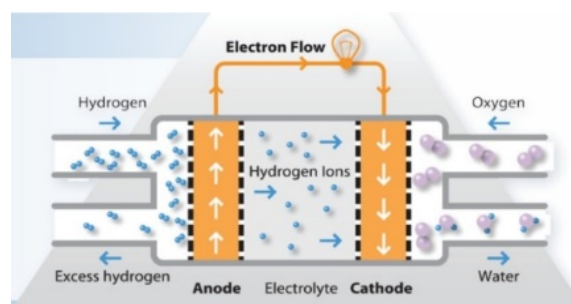


Figure 4. Scheme of Proton Exchange Membrane Fuel Cell - PEMFC [9].

4.2. Direct Methanol Fuel Cell – DMFC

Physicochemical characteristics:

- Electrolyte: acid polymer membrane (PEMFC),
- Catalyst: platinum–ruthenium on the anode and a platinum catalyst on the cathode,
- Fuel: hydrogen atoms from liquid methanol instead of hydrogen,
- Operation temperature range: 60°C to 130°C,
- DMFCs – suitable for applications with power outputs less than 250 W.

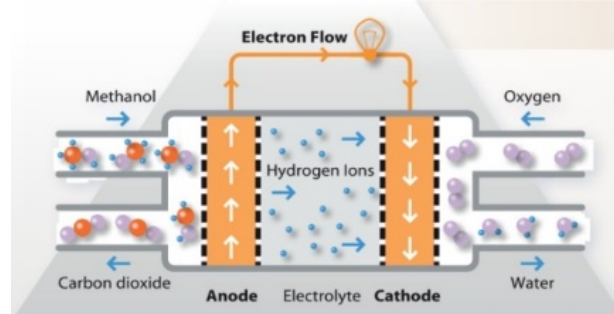


Figure 5. Scheme of Direct Methanol Fuel Cell – DMFC [9].

4.3. Solid Oxide Fuel Cell – SOFC

Physicochemical characteristics:

- Electrolyte: solid ceramic, such as stabilised zirconium oxide,
- Catalyst: a precious metal catalyst is not necessary,
- Fuel: can run on hydrocarbon fuels such as methane or propane,
- Operation temperature range: 800°C to 1000°C,
- Best run continuously due to the high operating temperature, typical in stationary power generation.

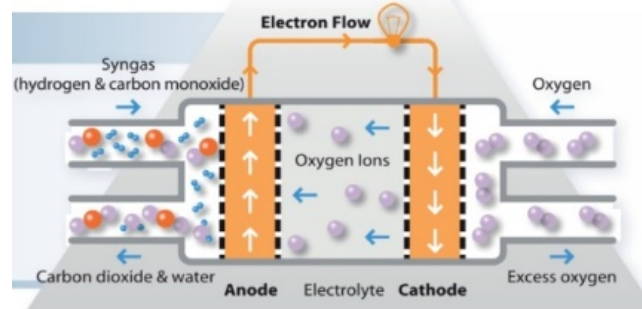


Figure 6. Scheme of Solid Oxide Fuel Cell – SOFC [9].

5. Efficiency of fuel cell UAV's propulsion system

The approximate values including also efficiency of different fuel cells being applied in UAVs are shown in table 2. It is visible that FC properties in the area of efficiency are relatively high. However if we take into account the efficiency of entire driving system results are much worse.

Table 2. Properties of fuel cells used at present in UAVs [10].

Fuel cell type	Fuel	Total efficiency [%]	Operation temperature [°C]	Fuel stack specific power [W/kg]	Entire system specific power [W/kg]
PEMFC	Hydrogen	40 – 60	30 – 100	> 500	> 150
DMFC	Methanol	20 – 30	20 – 90	> 70	> 50
SOFC	Hydrocarbon	30 – 50	> 500	> 800	> 100

The scheme of elements included in present fuel cell propulsion system is presented in the figure 7. Generally like “classic” systems containing combustion engine the fuel cell propulsion has comparable low overall efficiency.

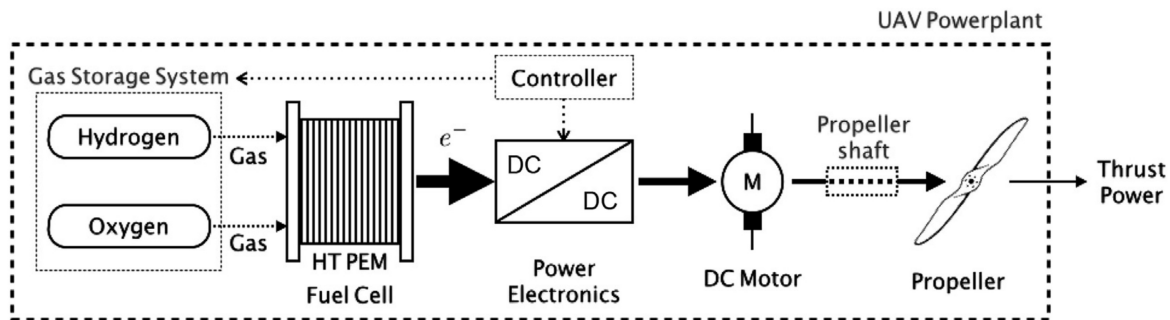


Figure 7. Scheme of the UAV electric propulsion system [11].

Taking into consideration full chain of energy conversion beginning from a fuel storage system through electrochemical processes, electronic control devices and ending in DC engine driving a propeller generating thrust the total efficiency reaches 25–30 % as it was shown in figure 8. On actual development level however, that propulsion system is promising because of mentioned features as for example low acoustic and thermal trace of UAV.

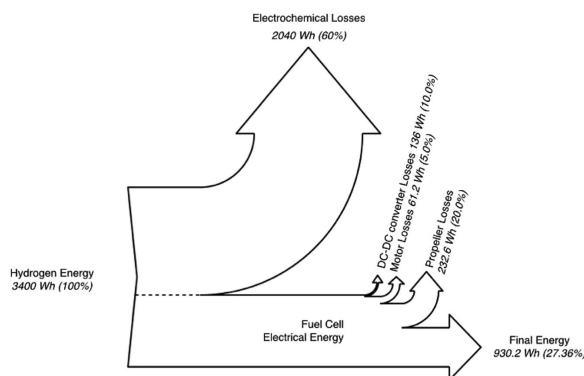


Figure 8. Diagram of energy losses in the different elements of UAV propulsion system [11].

There are at present several areas of interest and intensive researches related to hydrogen storage methods and on-board generation. That problem needs to be solved in the close future particularly in HALE UAVs' propulsion:

- Hydrogen is at present the basic fuel for fuel-cells driven UAVs but the low density of hydrogen at standard conditions (0.089 kg/m^3) effects in issues of its efficient storage being the essential problem for UAVs,
- The most natural way of hydrogen storage seems to be compression. This method requires use of the relatively light composite bottles sustaining pressure of about 70–80 MPa. The other alternative methods are hydrogen storage in liquefied state requiring however, criostatic vessels and hydrogen generation from chemical compounds for instance water solution of NaBH_4 ,
- The next important issues of fuel cells ought to be solved are functional robustness, resistance to operating pressure related to flight altitude and proper water management of fuel cell. Water management is particularly related to PEM built with sulphated fluorine-polymer membranes (e.g. Nafion type). Good hydration is a condition of correct work of these membranes. Dried membrane has high electric resistance effecting in bigger losses and heat release [12, 13, 14]. This is the reason why humidification of gases taking part in chemical reaction in fuel cells is applied,

- Hydrogen fuel cell propelled drones have an advantage over battery driven ones because the endurance of flight is limited only by hydrogen supply but the necessity of periodic refuelling still remains.
- Fuel storage techniques affect the refuelling possibilities of drones what is especially important for military applications where in field conditions, the fast refuelling may be essential for mission success.

The comparison of chosen hydrogen storage methods is presented in table 3 where the data for physical properties of stored hydrogen do not include the volume and mass of tank and whole fuel system.

Table 3. Comparison of hydrogen storage methods [15].

H ₂ Storage Method	H ₂ Mass Percentage [%]	Specific Energy [Wh/g]	H ₂ Density [g/dm ³]	Energy Density [Wh/dm ³]
Compressed Gas (35–70 MPa, 25°C)	100	20	23–39	450–770
Cryogenic Liquid (0.35 MPa, T= -248°C)	100	20	64	1270
Aqueous NaBH ₄ (0.1 MPa, 25°C)	4.0–6.4	0.8–1.3	41–64	810–1270

6. Example of present application of FC to small multicopter UAV

Representative example of contemporary efficient feeding systems basing on compressed hydrogen can be the 1800W H1-Fuel Cell elaborated by MMC (MicroMultiCopter Aero Technology Co. Ltd) from Shenzhen, China. That fuel cell system is designed for long endurance UAVs and has been applied among others to the MMC's HyDrone 1550 multicopter shown in figure 9. According to producer statement H1-Fuel Cell allows professional drones to achieve endurance up to 150 min.



Figure 9. MMC's HyDrone 1550 multicopter equipped with 1800W H1-Fuel Cell [16].

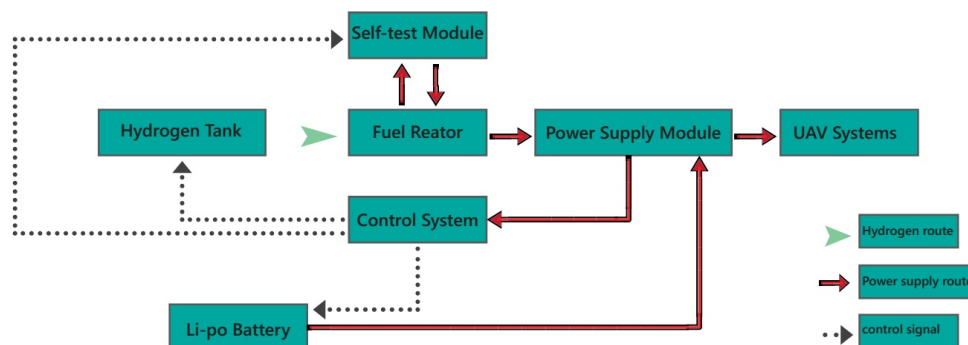


Figure 10. Scheme of MMC's H1-Fuel Cell 1800W hydrogen feeding system [17].



Figure 11. Fuel cell stack and compressed hydrogen bottle [18].

H1- Fuel Cell feeding system presented in figure 10 consists of several essential elements – fuel cell stack, control system, hydrogen tank and auxiliary Li-Po battery. Fuel cell stack is made of 60 graphite plates cooled by four controlled fans. Storage system consists of compressed hydrogen tank with equipment i.e. air valve and high pressure sensor. Control system consists of two solenoid valves, low pressure sensor, radio and personal computer. MMC declares up to 1000 hours lifespan of that system as well as low (< 8 MPa) and redundant (> 37 MPa) hydrogen pressure protection. Fuel cell stack together with compressed hydrogen tank (bottle) are shown in figure 11. Chosen parameters of MMC's H1-Fuel Cell system are presented in table 4.

Table 4. Chosen parameters of MMC's H1-Fuel Cell system [17].

Parameter	Data
Nominal output voltage	33.3–60 V
Nominal power rating	1800 W
FC height	278 mm
FC Width	218 mm
FC Depth	129 mm
FC Weight	5.2 kg
Operating temperature	$-10^{\circ}\text{C} - +40^{\circ}\text{C}$
H ₂ fuel purity	$> 99.99\%$
H ₂ storage pressure	1.5–35 MPa
H ₂ refueling time	± 40 min
Fuel tank capacity	9 dm ³
Fuel tank weight	3.1 kg
Auxiliary Li-Po battery capacity/weight	3000 mAh / 250 g

7. Conclusions

Big attention turned towards fuel cells as the source of propulsion of future drones is justified by the results of works running by R&D centres of aviation industry. Great interest and financial outlays carried by aviation giants like Boeing or Lockheed Martin leading researches with cooperation with NASA and DARPA seems to be symptomatic. Tests are carrying out usually on existing before proven UAVs being equipped with experimental fuel cell technology. Many firms being founded specially for drones' manufacturing are contributing to development of their propulsion systems including fuel cells. The trend for use hybrid propulsion systems consisting of fuel cells and batteries or fuel cells and heat engines (not mentioned in this article) has the temporary character until the reliable fuel cell systems are developed.

There are visible several issues concerned with fuel cells application to drones' propulsion requiring a solution in future:

- effective hydrogen storing methods (as compressed gas or in chemical compounds),
- light and highly efficient fuel cells,
- development of the high specific energy batteries for basic of auxiliary power supply,
- elaboration of fuel cell systems designed to correct work on high altitude in conditions of low temperature and low oxygen concentration, what enable the HALE UAVs to be equipped with

such energy source,

- control algorithms for optimal energy utilization in hybrid propulsion systems enabling achievement of long endurance flights.

Probably in relative close future the “mature” constructions of fuel cell systems will drive the small drones without batteries or heat engines support.

References

- [1] Dutczak J 2014 Turbine and turbojet engines for propulsion of contemporary drones, *J. Logistics* **6** (2014)
- [2] Dutczak J 2014 Combustion engines for propulsion of contemporary drones, *Combustion Engines and Ecology* (Cracow University of Technology) p 63-82, ISBN 978-83-7242-763-2
- [3] Dutczak J Heavy fuel engines. *Combustion Engines* 2015, **163**(4) p 34-46, ISSN 2300-9896
- [4] Dutczak J 2015 Nonconventional propulsion sources of drones, *J. Logistics* **3** (2015) <https://www.gov.uk/government/case-studies/bladon-jets-innovative-mobile-and-low-cost-generator-takes-off>
- [5] Dutczak J 2016 Micro Turbine Engines For Drones Propulsion (Cracow University of Technology) p 71, ISBN 978-83-7242-897-4
- [6] <https://www.droneii.com/drone-energy-sources>
- [7] Lapena-Rey N, Blanco J A, Ferreyra E, Lemus J L, Pereira S, Serrot E 2017 A fuel cell powered unmanned aerial vehicle for low altitude surveillance missions, *Int. J. Hydrogen Energy* **42** (2017) 6926-6940
- [8] Sharaf O Z, Orhan M F 2014 An overview of fuel cell technology: Fundamentals and applications, *Renewable and Sustainable Energy Reviews* **32** (2014) pp 810–853
- [9] Fuel cell basics - technology types 2012, <http://www.fuelcelltoday.com>
- [10] Gong A, Verstraete D 2017 Fuel cell propulsion in small fixed-wing unmanned aerial vehicles: Current status and research needs, *Int. J. Hydrogen Energy* **42** (2017) pp 21311–33
- [11] Renau J, Lozano A, Barroso J, Miralles J, Martin J, Sanchez F, Barreras F 2015 Use of fuel cell stacks to achieve high altitudes in light unmanned aerial vehicles, *Int. J. Hydrogen Energy* **40** (2015) pp 14573–14583
- [12] Liso V, Araya S, Olesen A, Nielsen M, Koer S 2016 Modeling and experimental validation of water mass balance in a PEM fuel cell stack, *Int. J. Hydrogen Energy* **41** (2016) pp 3079–92
- [13] Ous T, Arcoumanis C 2013 Degradation aspects of water formation and transport in proton exchange membrane fuel cell, *J. Power Sources* **240** (2013) pp 558–82
- [14] Kim J, Kim D M, Kim S Y, Nam S W, Kim T 2014 Humidification of polymer electrolyte membrane fuel cell using short circuit control for unmanned aerial vehicle applications, *Int. J. Hydrogen Energy* **39** (2014) pp 7925–30
- [15] Advanced propulsion for small unmanned aerial vehicles – The role of fuel cell-based energy systems for commercial UAVs, *Ballard White Paper* (2017)
- [16] <http://www.mmcuav.com/drones/hydrone1550/>
- [17] MMC H1-FuelCell brochure.pdf
- [18] <http://www.uasvision.com/wp-content/uploads/2017/07/H1-fuel-cell-MMC.jpg>