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FUEL CELLS AS ALTERNATIVE POWER FOR UNMANNED AIRCRAFT SYSTEMS – CURRENT SITUATION AND DEVELOPMENT TRENDS

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Abstract:

The study provides a detailed analysis of power systems for unmanned aerial vehicles with a spotlight on advantages and disadvantages of their solutions. The main theme focuses on a possibility of using fuel cells in UAV systems with emphasis on technological aspects. Presented types of fuel cells, along with the most essential characteristics, show their alternatives in practical use. The procedure describes a current development for unmanned aerial platforms using fuel cells. After evaluation of available solutions, preferred cell types are proposed to be used in these systems. In respect to it, unmanned aerial vehicles profiles present chosen results, their characteristics, selection criteria and development.

Keywords: *Fuel cells, unmanned aerial vehicles, energy storage, power supply*

1. INTRODUCTION AND TECHNOLOGICAL BACKGROUND

1.1. Fuel cells basic principle

Fuel cells are electrochemical devices that generate electricity converting chemical energy stored in hydrogen fuel using oxidant (usually oxygen gas from the air) and keep operating as long as fuel and oxidizer are supplied.

When fuel cells are fed with hydrogen the only side products of the electrochemical reaction in fuel cells are water, heat and low oxygen-containing exhaust air (Gonzalez-Espasandin, 2014).

Fuel cells produce low voltages (single cell around 0.6÷0.7V) but since they are modular devices, they can be assembled into a fuel cell stack in order to reach the desired amount of electrical power required for most UAV applications. The number of individual cells and their arrangement determines the electrical output of the stack. Increasing the number of cells in a stack increases the voltage while increasing the surface area of the cells increases the current. Their power ranges from micro to megawatts making them suitable for a multiplicity of applications.

In addition to stack fuel cell systems consist of a number of components. The important part of the system is a balance of plant that ensures operation, functionality and electrical energy distribution of the specific application. Elements of plant balance include thermal and humidification management, electric power conditioning, interface functions and a fuel processor if needed.

All individual cells consist of three basic components: an anode, a cathode, and electrolyte. The anode and the cathode is separated by electrolyte allowing protons to pass through it. Electrons flow through an external electrical circuit producing an electric direct current that can power a load. The specific reactions that take place at the anode, cathode and ions presented in the fuel cell depend on the type of a fuel cell (Spencer, 2013).

The main advantages of fuel cells are their low greenhouse gases emissions, high efficiency, modularity, fuel flexibility, a range of applications, a low level of noise generation, weight due to hybridization possibility to lower fuel cell power and weight, a low infrared signature and also reversibility in RFC Regenerative Fuel Cell. The main advantage of applying RFC is their potential of reaching higher specific energy densities than any advance battery systems, which makes them suitable for applications that require storage of a large amount of energy.

Hybrid energy storage and propulsion systems for spacecraft, high altitude long endurance solar aircraft (HALE), vehicles, backup power and remote off-grid power sources are the applications where RFC can be implemented (Revankar, 2013).

The theoretical specific energy of hydrogen and oxygen combined in an electrochemical reaction is 3.6 kWh/kg. Even the mass of hydrogen and oxygen storage tanks, as well as RFC itself, are taken into account. The overall specific energy density about 1kWh/kg is still higher than that of any advance battery system (Barbir, 2005).

However, there is also a need for improvement in weight, volume, cost reduction, sensitivity of the electrode catalyst to poisons and the poor hydrogen generation infrastructure in order to deliver fuel for fuel cells, which are already in use (Spencer, 2013).

There are numbers of applications where fuel cells are advantageous, such as: auxiliary power units for ground vehicles, ships, and aircraft, unmanned air, ground, and underwater vehicles (UXVs), remote sensors and surveillance, vehicular or remote applications, boats, submarines, backup power, soldier wearable and portable power, distributed stationary power, ground support equipment, light-duty vehicles, mobile electric power, personnel transport and cogeneration (Gross, 2011).

1.2. Current power supply systems for UAVs

Unmanned aerial vehicles are equipped with different types of power units. In order to choose a valuable design, it is important to base the judgement on system types, speed and endurance. Unmanned aerial systems became rapidly popular and solutions are used in various surveillance and monitoring within the areas of air, ground and underwater. Over 90% of civilian UAVs are powered by battery systems. The current state of Lithium batteries shows that they are already common in use. NiCad and NiMH batteries are now used very rearly in every day use as well as in UAVs. The reason for the popularity of lithium batteries is their high energy density. For the same reason, there is an ongoing intensive research of use of fuel cells in unmanned systems. It is important to identify current solutions on the market.

Batteries are currently the most popular way to power UAVs. Batteries composed of a series of cells from one to several and may be a series or parallelly connected. Individual cells or a single cell battery in Lithium Ion or LiPoly is between 3.2 to 3.7 volts, depending on chemistry. There are lithium ion (Li-ion), lithium iron phosphate (LiFePO4), lithium polymer (LiPo) and lithium titanate batteries. Batteries are relatively heavy, and that is one of the biggest problems. Batteries are currently limited to 150 – 200 Wh/kg and are expected to show an increase of up to 300 Wh/kg within the next few years. The most important research and development challenges are: an improvement of specific energy and power (in order to achieve independent electric drive range), extending the battery lifetime, lifecycle assessment and recycling processes and improvement of economic parameters and prices. The most popular systems are:

- LiCoO2 Lithium Cobalt Oxide battery has a high energy density but also a low discharge rate and flammable safety hazard.
- LiFePO4 Lithium Iron Phosphate battery gets lower energy density but it is safer with a higher discharge rate and longer lifetime. They are unfortunately heavier than other lithium batteries with an equivalent capacity.
- LiPo Lithium Polymer battery consists of a flat pack with a polymer separator, higher discharge rates and lower energy density. LiPo batteries use normal lithium ion chemistries, the polymer separators reduce capacity but permit higher discharge rates. Their life span is 600 nominal discharge cycles.
- Lithium Ion battery has a very high energy density, up to twice the energy density of a LiPo. However, the problem lies in a very low discharge rate, i.e. about 2C. Another advantage of lithium ion batteries is their operation to over a thousand charge cycles. They also have a large potential to further increase energy density by using advanced anode and cathode materials. Lithium ion batteries are vulnerable to short-circuiting and overcharging. Lead acid, Ni-Cd and Ni-MH batteries perform safely even after short-circuiting and overcharging because they have low energy capacity and use inflammable electrolyte. However, when a lithium ion battery short circuits, high electricity flows are created and the battery temperature increases to several hundred degrees within seconds, heating up neighboring cells and resulting in the entire battery combustion reaction.

The lithium ion (Li-Ion) and the fuel cell (FC) technology comparison is presented below based on Luo et al., 2015:

- Energy density (Wh/L):
  - Li-Ion: 200–500 (Chen et al., 2009);
  - FC: 500–3000 (Chen et al., 2009);
- Power density (W/L):
  - Li-ion: 1500–10,000 (Technical report, 2011);
  - FC: 500+ (Chen et al., 2009);
- Specific energy (Wh/kg)
  - Li-Ion: 75–200 (Chen et al., 2009);
  - FC: 800–10,000 (Chen et al., 2009);
- Specific power (W/kg):
  - Li-ion: 150–315 (Chen et al., 2009), 500–2000 (Hadjipaschalis at al., 2009);
  - FC: 500+ (Chen et al., 2009), 5–800 (Winter, Brodd, 2004);
- Power rating (MW):
  - Li-Ion: 0–0.1 (Chen et al., 2009), 1–100 (Rastler, 2010);
  - FC: up to 50 (Chen et al., 2009) and more according to Fuel Cell Energy Solutions GmbH, 12/2012;

- Daily self-discharge (%):
    - Li-Ion: 0.1–0.3 (Chen et al., 2009), 1 & 5 (Díaz-González F et al., 2012);
    - FC: Almost zero (Chen et al., 2009);
- Lifetime (years):
    - Li-Ion: 5– 15 (Chen et al., 2009);
    - FC: 5–15 (Chen et al., 2009), 20+(Smith, 2000);
- Cycling times (cycles):
    - Li-Ion: 1000–10,000 (Chen et al., 2009), up to 20,000 (DTI Report, 2004);
    - FC: 1000+ (Chen et al., 2009), 20,000+ (Smith, 2000);
- Discharge efficiency (%):
    - Li-Ion: 85 (Shoenung, 2001);
    - FC: 59 (Shoenung, 2001);
- Cycle efficiency (%):
    - Li-Ion: 90–97 (Chen et al., 2009), 75–90 (Rastler, 2010);
    - FC: 20–50 (Chen et al., 2009), 45–66 (Schaber et al., 2004);
- Response time:
    - Li-Ion: Milliseconds, <1/4 cycle (Beaudin et al., 2010);
    - FC: Seconds, <1/4 cycle (Shoenung, 2001);
- Suitable storage duration:
    - Li-Ion: Minutes–days (Chen et al., 2009), short-to-med. Term;
    - FC: Hours–months (Chen et al., 2009);
- Discharge time at power rating:
    - Li-Ion: Minutes–hours (Chen et al., 2009);
    - FC: Seconds–24 h+ (Chen et al., 2009);
- Power capital cost ($/kW):
    - Li-Ion: 1200–4000 (Chen et al., 2009), 900–1300 (Hadjipaschalis at al., 2009), 1590 (Rastler, 2010);
    - FC: 500 (Shoenung, 2001), 1500–3000 (Mekhilef et al., 2012);
- Energy capital cost ($/kW h):
    - Li-Ion: 600–2500 (Chen et al., 2009), 2770–3800 (Rastler, 2010);
    - FC: 15 (Shoenung, 2001), 2–15€/kWh (Kaldellis, Zafirakis, 2007);
- Operating and maintenance cost:
    - Li-Ion: -
    - FC: 0.0019–0.0153 $/kW (Mekhilef et al., 2012);
- Maturity:
    - Li-Ion: Demonstration;
    - FC: Developing/Demonstration.

In the Figure 1.2.1 batteries and AEROPAK fuel cell system (www.hes.sg, 2014) comparison assuming 200W constant power over time is presented.

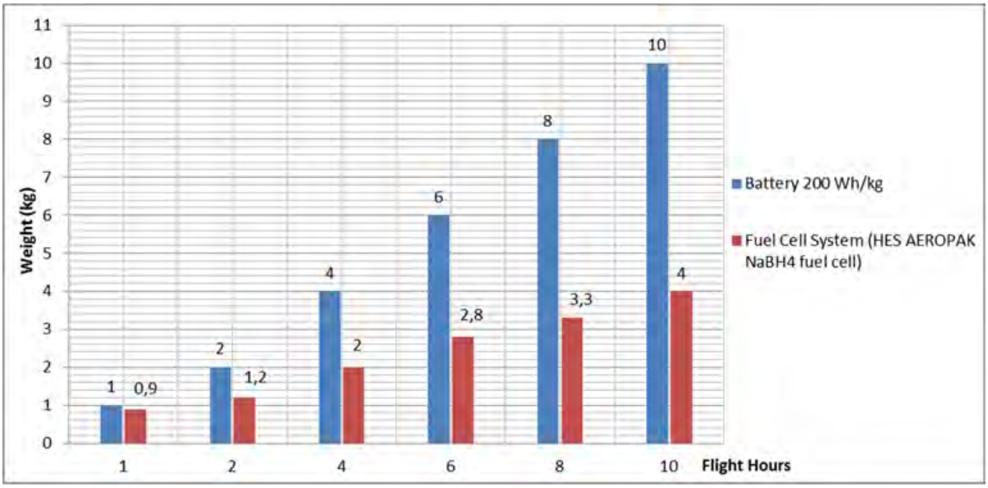


Figure 1.2.1 Batteries and AEROPAK fuel cell system comparison assuming 200W constant power over time based on Horizon Energy Systems data (www.hes.sg, 2014).

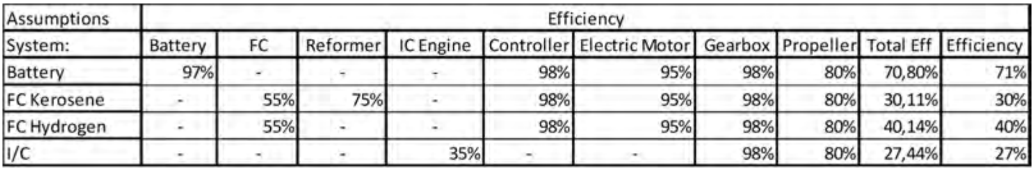
Combustion engines are lightweight, have high power and range, but they are not without drawbacks. The problem is that they are loud, and the noise of the engine makes it easier to detect. In addition, the internal combustion engines used for a propulsion drone emit a lot of heat so that the machine can be traced by such detectors as infrared detectors used in homing rockets. The problem is also emission of harmful gases. Currently used combustion engines, can be divided into the following groups:

- Reciprocating engines: distinction can be made by the combustion process (spark-ignition engines, diesel engines, etc.), cycle (two-stroke and four-stroke engines), intake manifold pressure (naturally aspirated and supercharged engines), air-cooled or water onces. Classification depends on the type of main cycle and its respective fuel, for example petrol or oil. One of the main weaknesses are vibrations that prevent torque to be delivered smoothly. Those motors are suitable for small and medium-sized UAV operations and short-range, so the Maximum Takeoff Weight (MTOW) is typically below 1,000 kg. Reciprocating engines are also harder for maintenance regarding complexity and fuel.
- Jet engines: they produce thrust and can be classified into jet engines and turbofans. Jet engines (jet-turbines or turbojets) are typical Fighting Vehicle Unmanned Air Vehicles (UAV). Turbofan are typical in high subsonic and are more frequently used in commercial aviation than in UAVs. If instead of thrust, power is supplied to the drive shaft of the propeller or rotor, they may be classified as turboprop engines, wherein the turbine engine is connected to a conventional drive. Jet engines are time efficient and produce less vibration than reciprocating engines but they are not suitable for operation at a low speed due to their high consumption at partial load.
- Other types of engines, such as Wankel engine, which is becomming more popular, due to smooth and simple operation and high durability (after their sealing and torsional vibration problems being currently solved) (Gonzalez-Espasandin, 2014).

Below, the article provides the comparison of different propulsion systems based on the publication of Hepperle, 2012 and assumes similar flight performance with 50kW of power for 2 hours of cruising. 100 kWh is assumed to be needed for the flight. From a number of possible configurations the four following typical propulsion systems are considered:

- battery powered system (Battery);
- kerosene fuel cell powered system (FC Kerosene);
- hydrogen fuel cell powered system (FC Hydrogen);
- internal combustion engine system (I/C).

Due to energy losses at each conversion step assumptions of on-board energy conversion efficiencies for components of discussed propulsion systems were made and are presented in Table 1.2.1. The efficiency comparison do not include the generation of electricity on the ground and the generation and distribution of fuel or electricity. The energy efficiency of a fuel cell is generally around 40–60% depending on a fuel cell type, but can be even higher with cogeneration – combined heat and power (CHP) systems, up to 85% (DOE Hydrogen Program, 2006). In the article the efficiency of fuel cell in a fuel cell powered system is assumed at the level of 55%. It can be seen that electric systems present the highest on-board system efficiency compared to internal combustion engine systems.



Assumptions	Efficiency									
System:	Battery	FC	Reformer	IC Engine	Controller	Electric Motor	Gearbox	Propeller	Total Eff	Efficiency
Battery	97%	-	-	-	98%	95%	98%	80%	70,80%	71%
FC Kerosene	-	55%	75%	-	98%	95%	98%	80%	30,11%	30%
FC Hydrogen	-	55%	-	-	98%	95%	98%	80%	40,14%	40%
I/C	-	-	-	35%	-	-	98%	80%	27,44%	27%

Table 1.2.1 Assumptions of energy conversion efficiencies for different on-board propulsion system components (Hepperle, 2012)

The comparison of the different propulsion systems depends on multiple factors, which need to be considered. The energy required for a flight is stored on-board and is defined by two parameters: the energy density – the energy per unit volume and the specific energy – the energy per unit mass, which are necessary in order to compare different power sources (Hepperle, 2012). For instance liquid hydrogen fuel has a higher specific energy than gasoline, but a lower volumetric energy density.

Based on the assumptions and according to the HyFish Flying Fuel Cell Demonstrator Project in order to obtain a flight performance, comparable to a battery-powered aircraft, the fuel cell system should have **3 kg/kW** gravimetric power density (www.smartfish.ch, 2011).

Other important factor is the mass of each type of propulsion system, which is strongly dependent on energy storage and conversion. Mass and efficiency comparison of propulsion systems providing a shaft power of 50kW for 2 hours based on the assumptions and the publication of Hepperle, 2012 is presented in the Figure 1.2.2.

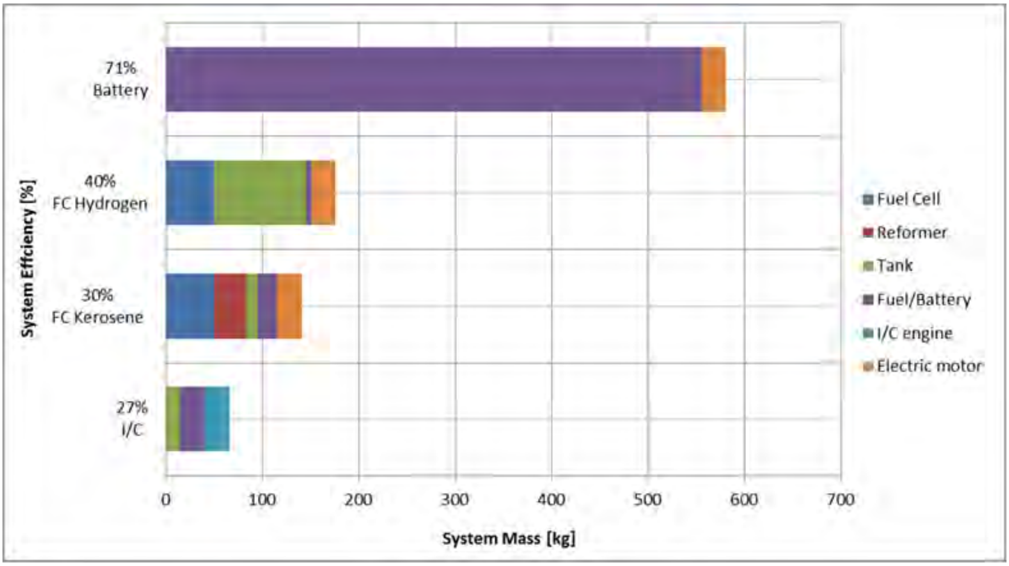


Figure 1.2.2 Mass and efficiency comparison of propulsion systems providing a shaft power of 50kW for 2 hours (Hepperle, 2012).

2. CURRENT APPLICATIONS OF FUEL CELLS SYSTEMS IN UAVS

2.1. Fuel cells technically practicable for use in unmanned flying platforms

The development of fuel cell technology reduces the weight per unit voulme at the same time increasing power and energy density. As a result, one of the biggest problems in aviation technology, i.e. mass, has been improved. Furthermore, the development in this area is constantly being implemented. This results in an advantage of fuel cell systems over advanced batteries in UAVs by lower life cycle cost, extended run times, a reduced size and weight. Fuel cells, practically, do not emit exhaust fumes except small amounts of water vapor, which means no emission as compared to traditional combustion engines. Moreover, heat emission is relatively small, in comparison with reciprocating engines, which makes planes practically untraceable by means of infrared devices. Additionally, the lack of moving parts increases reliability, simplifies service and decreases vibration (Dudek, 2013). Generally, fuel cells can be classified according to two parameters: the type of electrolyte and temperature. Because of the electrolyte, we can distinguish:

- DMFC - Direct Methanol Fuel Cell
- PEMFC – Electrolyte Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell
- AFC – Alkaline Fuel Cell
- PAFC – Phosphoric Acid Fuel Cell
- MCFC – Molten Carbonate Fuel Cell
- SOFC – Solid Oxide Fuel Cell

An important element to use fuel cells is their operating temperature, size and weight. Given these parameters, precludes the use of AFC, PAFC and MCFC cells in unmanned systems. If we consider the use of DCFC, we must take into account the toxicity of methanol. In addition, the anode has a limited resistance to carbon monoxide, which is formed during the oxidation of methanol. DCFC cell efficiency is substantially lower than the PEMFC. Currently on the market the most advanced and widely available are PEMFC. Their working temperature is below 100°C, so that they can be used in UAV systems (Stolten, 2012). The current SOFC operating temperatures are above 800°C, which are considered to be used as a system support for equipment in unmanned aerial vehicles.

Polymer Electrolyte membrane fuel cell (PEMFC) system performs high energy, integrated in the rechargeable energy systems (Bradley, 2007). Their main advantage is low temperature (80-160°C) during operations in transportation and portable devices with high power density. Cells are able to achieve different orientations and do not utilize corrosive fluids (Larmine, 2003). Mostly characterized with a high efficiency, fast responses to loads, a reliable output of power for vehicular and mobile applications. PEMFC which is propelled by a fuel in form of clean hydrogen, that enables the use for maneuverable and high endurance UAVs for surveillance applications. The above mentioned values allow to build a light and low cost vehicle with small volume systems (Gonzalez-Espasandin, 2014).

Solid Oxide Fuel Cell (SOFC) system is a subsidiary part of the PEMFC but having a different weight. For that reason, the type of fuel cell is of a smaller interest than PEMFC. Another aspect is temperature for operating the fuel cell, which ranges from 800-1,000°C and generates higher costs of operation, due to different material equipment. However, currently conducted researches aim at developing SOFC systems which can operate at the temperature of 700°C. The advantage of SOFC is definitely high operating temperature, which improves efficiency for base load power. Secondly, the solid electrolyte boosts conductivity. In the opposite of PEMFC, the fuel used in this solution, kerosene has better reforming and cleaning properties. However, this system performance for UAVs is not favored at a current stage.

2.2. Research and Development of Fuel-cell-powered unmanned aerial vehicles (UAV)

Currently, the development of aviation sector is moving towards More Electric Aircraft (MEA) concept concerning reduced fuel use and emissions on ground and in flight operations by improving electrical power generation technologies. The main idea of this MEA architecture is to replace pneumatic and hydraulic systems onboard aircraft by electrical power including fuel cell applications. Power distribution subsystems onboard commercial aircraft, ram air turbine (RAT) and auxiliary power units (APU) can be replaced by fuel cell technology and much of the research and development in commercial application has been already done (Spencer, 2013).

Regarding aerospace, the first fuel cell-powered aircraft manufactured by NASA was the Apollo Space Shuttle (alkaline fuel cell) and Gemini spacecraft (PEM fuel cell) in ‘60s.

For the manned aircraft, several projects with fuel cell power solutions have been implemented. In 2005 FASTec/ATP conducted the first flight of the fuel cell-battery hybrid power E-plane. In February 2008 Boeing Commercial Airplanes together with European Partners conducted experimental flight tests in Spain of a manned airplane powered only by a fuel cell and lightweight batteries. The Fuel Cell Demonstrator Airplane used a PEM provided by Intelligent Energy and lithium-ion battery to gain altitude and then cruised using only fuel cell power. In 2009 DLR presented Antares DLR-H2 fuel cell manned aircraft, the flying test platform. Next, in 2011, DLR, Airbus and Lufthansa Technique introduced the A320 ATRA aircraft equipped with a fuel cell-powered electric nose wheel using only fuel cell power. European Community “ENFICA-FC” project conducted the first flight of fuel cell – hybrid airplane in 2010 (www.fuelcell.org, 2014).

From all types of fuel cells PEM FC have been most commonly used in UAVs. The number of papers and reports from fuel cell manufacturers, component suppliers, fuel cell integrators, universities, research centers and government agencies express an interest and perspective in a promising research for the use of fuel cell in UAVs. Research on the use of fuel cells in small, unmanned aircraft has already been underway for a number of years. There have been several fuel-cell-powered unmanned aerial vehicles (UAV) (www.protonex.com, 2014). Some of them are described below:

- Helios (Aerovironment, NASA, Quantum Technologies, 2003) – photovoltaic-fuel cell hybrid powered UAV;
- Hornet FC MAV (DARPA – Defense Advanced Research Projects Agency sponsored research contract, 2003) – micro aerial vehicle, powered by a fuel cell;
- Global Observer UAS (Aerovironment, 2005) – liquid hydrogen storage;
- Spider-Lion (U.S. Naval Research Laboratory, Protonex, 2005) – a test flight of 3 hours and 19 min. with H2 fuel consumption of 15 g H2;
- Fuel Cell Puma (Protonex, US Air Force Laboratory, Naval Research Laboratory, Millennium Cell, 2007) – with a metal hydride onboard hydrogen storage flew for 7 hours and then for 9 hours (Stolten, 2010);
- Pterosoar (Cal State MFDC Lab, Oklahoma State University, Horizon Fuel Cell Technologies,2007) – mini-UAV, with compressed hydrogen storage flew for 3 hours of 128 km distance (Stolten, 2010);
- HyFish fuel cell jet wing UAV (DLR German Aerospace Agency, Horizon Fuel Cell Technologies, 2007) – with compressed hydrogen storage;
- Endurance UAV (University of Michigan, Adaptive Materials, Inc., 2008) – flew for more than 10 hours of 159 km distance (Stolten, 2010);
- Ion Tiger (U.S. Naval Research Laboratory, The University of Hawaii, HyperComp Eng., Protonex, 2009);
- Mako UAS (U.S. Naval Research Laboratory, Pennsylvania State Univesrity, Kuchera Eng., L3 Communications/BAI, Jadoo Power, 2009) – Fuel cell system provided 63W to the avionics and to the nose camera and video transmitter payload during the entire flight of more than 1 hour duration (Fuel Cell Bulletin, 2009a);
- Raven UAV (Protonex, AeroVironment, 2009) – achieved a flight time of 3 hours, doubled the endurance of battery powered version;
- Boomerang (Israel-based BlueBird Aero Systems, Horizon Fuel Cell Technologies, 2009) – flew for 9 hours, 9kg UAV, the world's first UAV powered by a commercially available fuel cell (Fuel Cell Bulletin, 2009b);
- Mini-helicopter (UTRC – United Technologies Research Center, 2009) – fuel cell powered helicopter achived 20-minutes flight duration with 2,3kg of payload;
- HALE Global Observer (Joint Capability Technology Demonstration program, 2010) – a high altitude and long endurance UAV with liquid hydrogen-powered internal combustion power plant ;
- Bird Eye 650 mini-UAV (Israel Aerospace Industries, Horizon Fuel Cell Technologies, 2010) – achieved a flight time of 6 hours and more than doubled the endurance of a battery-powered version;
- EAV-1 UAV (Korean Aerospace Research Institute KARI, South Korea's Uconsystem, Horizon Fuel Cell Technologies, 2010) – achieved a flight time of 5 hours, 3 hours longer than the battery-powered version;
- Skylark UAV (Elbit Systems, Horizon Fuel Cell Technologies, 2010) – with compressed hydrogen storage;
- CIAM-80 mini UAV (CIAM Baranov Centraal Institute of Aviation Motors, Horizon Energy Systems, 2010) – with compressed hydrogen storage, flew several minutes;

- Stalker XE UAS (Boeing, Lokheed Martin, Adaptive Materials Incorporated, 2011) – flew for more than 8 hours, powered by SOFC on propane fuel with LiPo battery;
- Faucon H2 (EnergyOr, 2011) – flew for more than 10 hours;
- Thunderbird (BlueBird Aero Systems, 2012);
- Phantom Eye HALE UAV (Boeing, NASA, 2012) – high altitude and long endurance UAV with liquid hydrogen-powered internal combustion power plant;
- Ion Tiger (U.S. Naval Research Laboratory, The University of Hawaii, HyperComp Eng., Protonex, 2009) – flew for 23 hours and 17 minutes in October with 2,3 kg payload and for 26 hours and 2 minutes in November by using compressed hydrogen stored at 350 bar (www.naval-technology.com, 2014);
- Ion Tiger (2013) – the UAV flew for 48 hours and 1 minute by using cyrogenic liquid hydrogen fuel in a NRL- developed cryogenic hydrogen fuel storage lightweight tank and delivery system. About 1kg fuel cell had rated power of 550W during testing (www.naval-technology.com);

3. PROTON EXCHANGE MEMBRANE FUEL CELL AS A SOLUTION FOR UNMANNED AERIAL VEHICLES

3.1. Explication of Proton Exchange Membrane Cell

Polymer electrolyte membrane fuel cells (PEMFCs) are the most promising source of energy for applications demanding low temperatures, pressures or rapidly changing power demands.

PEM fuel cell can be beneficial for different application and UAVs, providing low temperature operations below 100°C, a possibility of using oxygen gas from the air and also having short start-up and shut-down times. Additionally, lower temperatures do not require the further balance of plant equipment to maintain high temperatures. Due to the low temperature operation of these cells, they can operate efficient and immediate after start-up, in ambient temperature conditions using an air-cooling system. This makes them ideal for UAV applications and with transient power needs.

Power system with the low temperature of proton exchange membrane fuel cell (PEMFC) is a potential competitor to the current power sources for transportation, mobile, portable and residential applications. Systems that require high energy density and operation at low power are desirable in unmanned aerial systems (UAVs). Currently, the specific energy density of a PEM fuel cell system is about 700–1,000Wh/kg providing higher endurance in UAVs compared to batteries (Romeo, 2013).

UAV low power systems operate at extreme ambient temperature, pressure and humidity conditions, which generates the need for improvement of water and thermal management strategies. Current development of low power systems is focused on requirements regarding high energy density, a reduced fuel consumption and emissions in order to improve overall weight/ mass ratio. Operations in extreme ambient conditions require quick start-up as well as high efficiency.

Micro PEM fuel cell systems are designed to provide low power output. Compared to high power fuel cells, micro fuel cell require different and individual treatment in design. System design and thermal management taking into account its weight and size restrictions. The difference lies not only in cell construction but also in the fact that micro fuel cells have smaller reactant distribution channels, specific electrolyte and materials, lower power density of membrane active area and bigger parasitic losses. PEM fuel cell application depends on durability and reliability of its technology. Further investigation and optimization is required.

PEM fuel cells use pure hydrogen as fuel. The core of the fuel cell consists of a membrane electrode assembly (MEA), which is placed between two flow-field plates and helps produce the electrochemical reaction needed to separate electrons. A typical MEA is composed of a Polymer Electrolyte Membrane (PEM), two catalyst layers, and two Gas Diffusion Layer (GDL). Each MEA consists of two electrodes, the anode and the cathode with a very thin layer of catalyst, separated by a PEM.

The flow-field plates provide hydrogen to the anode and oxygen to the cathode. The platinum catalyst layer increases the rate of reaction at both anode and cathode, and promotes hydrogen separation into protons and electrons. Air flows through the channels in flow field plates leading directly to the cathode. The free electrons, produced at the anode, are conducted in the form of a usable electric current through the external circuit. The hydrogen protons diffuse through the proton exchange membrane and combine with oxygen from the air and electrons which return from the external circuit to form water and heat.

3.2. PEM cell availability for unmanned systems

Fuel cell system for aeronautical applications needs to meet special requirements and safety issues, which are mostly higher than the requirements for stationary and for automobile applications. All necessary components of fuel cell system should operate properly during UAV operation in different and rapidly changing conditions regarding: altitude, temperature, pressure, humidity, vibrations, shock and radiation.

There are many fuel cells designed for application working on ground without the need for dynamic changes and in relatively stable environmental conditions, but there are some commercially available fuel cell systems suitable for UAV. A couple of them are described below:

- Horizon Fuel Cell Technologies (HES) in Singapore offers fuel integrated systems and ultra-light fuel cells designed especially for UAVs. Additionally, custom engineering solutions are also available in variety of configurations depending on range of power and type of UAV. An integrated fuel cell system has two options: 200W/ 900Wh (2 kg take-off weight/1.5 kg landing weight) and 200W/ 1,800Wh (3 kg take-off weight/1.5 kg landing weight) with an "on-demand" hydrogen generating unit based on NaBH4 feedstock. Ultra-light fuel cells are available with power of 200W, 500W, 1,000W and with pressurized hydrogen vessel systems. Horizon Fuel Cell Technologies had developed the liquid chemical fuel–integrated fuel cell system called AEROPAK, which consist of three sections: a fuel tank with hydrogen-rich NaBH4 mixture, a hydrogen generation system and a fuel cell (www.hes.sg, 2014).

AEROPAK system was already used in the previous projects on UAV demonstration and test, which include Pterosoar, HyFish fuel cell jet wing UAV, Boomerang, Bird Eye 650 mini-UAV, EAV-1 UAV, Skylark UAV, CIAM-80 mini UAV.

- Protonex provides unattended, a reliable and durable source of power for a large spectrum of applications including UAVs (www.protonex.com, 2014)

The Protonex system was already used in the previous projects on UAV demonstration and test flights, which include: Fuel Cell Puma, Spider-Lion, Ion Tiger and Raven UAV.

- EnergyOr provides aerospace fuel cell system solutions with 1,790 Wh at 310 W (www.energyor.com, 2011)

EnergyOr system was already used in the previous project Faucon H2 on UAV demonstration and test flights.

- Jadoo Power Systems, Inc. develops and manufactures power and energy storage systems for military and commercial markets (www.bloomberg.com, 2014).

Jadoo Power system was already used in the previous project Mako UAS on UAV demonstration and test flights. Considering fuel for UAV, the average cost of production of hydrogen for fuel cells ranges between 2,2 - 2,8 EUR/kg, while the wholesale price of gasoline is about 1,2 EUR/kg. Given the calorific value of hydrogen and gasoline (OH2 = 120 MJ/kg and Ogas = 42 - 44 MJ/kg), thermal efficiency of engines and fuel cell (ηe = 0,25 - 0,30 and ηfc = 0,4 - 0,5), we obtain the cost of hydrogen fuel about two times lower than conventional fuels. Aircraft operating costs with the use of propulsion system and fuel cells will be much lower, consequently more hydrogen energy production will be developed.

4. CONCLUSIONS

Research analysis in recent years shows a development of fuel cells to proper means of transportation, such as: electric cars, ships and planes. The cost of hydrogen use is comparable to the price of petrol. A fuel cell would be approximately five times lighter than the current battery solution thus providing a similar range of flight. The difficulty in the latter case lies in low specific power drive units with fuel cells (specific power = power / weight power plant with fuel tank) and insufficient specific energy of the drive unit. Technological development of fuel cells progress in the field of material science has allowed to reduce the weight of a fuel cell unit by enabling the first practical attempt to use them in aerospace. A reason for the tests are the advantages of fuel cells in comparison with internal combustion engines in following applications: fuel cells operate silently by using particular predisposes in unmanned surveillance aircraft. They do not emit exhaust gases and have a low heat emission, which makes it virtually impossible to identify and destruct devices using infrared radiation, especially at night. Due to the lack of moving parts, vibrations are reduced, the maintenance is simplified, their reliability is increased and high efficiency of fuel cells is conserved. In relation to the competitive electric power from batteries, electrochemical fuel cell system weights more than 3.5 times less than the battery lithium-ion cells, 8 times less than the battery NiMH cells and 16 times less than the team of lead-acid batteries (Broussely, 2007). PEMFC seems to be the most appropriate for this purpose due to the accomplished high operational parameters, reliability and commercial availability.

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OGNIWA PALIWOWE JAKO ALTERNATYWNE ZASILANIE BEZZAŁOGOWYCH SYSTEMÓW LATAJĄCYCH (BSL) – OBECNA SYTUACJA I KIERUNKI ROZWOJU

Abstrakt:

Opracowanie zawiera szczegółową analizę systemów zasilania w bezzałogowych statkach powietrznych, charakterystykę, wady oraz zalety poszczególnych rozwiązań. Głównym tematem jest możliwość zastosowania ogniw paliwowych w systemach UAV. Nacisk położony jest na aspekty technologiczne. Przedstawione są typy ogniw paliwowych wraz z najważniejszymi cechami, oraz ich analiza pod kątem możliwości wykorzystania praktycznego. Przygotowano również opracowanie przedstawiające platformy bezzałogowe obecnie wykorzystujące ogniwa paliwowe. Po wnikliwej ocenie dostępnych rozwiązań, wykazano, którego typu ogniwo obecnie preferowane są do wykorzystania w systemach UAV. Następnie przedstawiono profil wybranego rozwiązania, charakterystykę, główne kryteria wyboru, kierunek rozwoju oraz podsumowanie.

Słowa kluczowe: Bezzałogowe systemy latające (BSL), magazynowanie energii, zasilanie, ogniwa paliwowe, PEM