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Evaluations on hydrogen fuel cells as a source of energy for specific operations category civil RPAS systems

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Abstract: - This paper is on the evaluation of hydrogen fuel cells as a mean to enhance RPAS systems performances in terms of reachable range and endurance to integrate them into controlled airspaces operatively and safely. Main steps to size a fuel cell system to feed electrical motors of a fixed wing RPAS capable of specific operations category are described in this article. Then, a more extensive parametric model of a fuel cell power line based on operative and safety requirements for medium range/medium endurance RPAS systems is presented and discussed.

Key-Words: - Controlled Airspaces, Endurance, Hydrogen Fuel Cell, Integration, Parametric Model, Range, Remotely Piloted Aircraft Systems (RPAS)

1 Introduction

Remotely Piloted Aircraft Systems (RPAS) are currently object of in-depth studies and researches on the issues related to their full integration into the civil controlled airspace with manned aircraft.

This is the natural consequence of the worldwide recognized utility of remotely piloted aerial systems for civil applications. In fact, they can be used to perform repetitive or dangerous aerial operations more quickly and with less effort and risks for the human operator. In Europe, the European Aviation Safety Agency (EASA) is directly committed to issue the general rules to achieve the full integration of RPAS with manned aircraft, aware of the economic potential of this new kind of aircraft.

Such integration will be gradual, but arranged within a limited time window and divided into two timeframes, performing a sort of accommodation towards the full integration [1]. The first temporal stage will be from present time to 2023. Due to the absence of regulations and industry standards to manage Instrumental Flight Rules (IFR) capable RPAS and due to their initial low number, during the first timeframe of integration, RPAS continue to be accommodated in controlled airspaces by means of Flexible Use of Airspace (FUA) / Advanced Flexible Use of Airspace (AFUA) techniques. For example, currently, this is a daily practice in Europe for military RPASs.

It is expected that the essential Standard and Recommended Practices (SARPS) will be issued by 2023. After this milestone, the second temporal stage will be from 2023 onwards. With the availability of rules, standards and supporting technology, RPAS will be integrated into controlled airspace as any other aerial user except for the fact that the pilot will not be on board. Consequently sense, detect and avoid equipment will be mandatory to interact with other manned or remotely piloted traffic. In fact, the most important basic requirement which lays at the basis of this complex regulatory and technical process of integration of RPASs into controlled airspace is and will be safety. More precisely, the integration of RPAS will not have to damage current level of safety reached by aerial transport [2].

On the base of the abovementioned guidelines, EASA is implementing a concept of operations for the integration of the RPASs with manned aircraft based on a risk-centric approach [3]. Three formal risk categories of operations have been defined by EASA in relation with RPASs sorties according to the level of risk o the considered operation: open, specific and certified, following an increasing level of operational risk. The open category refers to RPAS systems of weight under 25 kg and authorized to fly until 500 ft of maximum altitude; the specific category will include RPAS systems capable of operations between 500 ft and flight level FL600 (i.e 60000 ft); certified category will include RPAS systems capable of flight operations comparable to those of current manned aircraft.

In addition, RPAS systems are entering an aviation scenario that is under modifications according to the following new elements:

- the International Civil Aviation Organization (ICAO) recommendations about safety and the adoption of a systematic way to manage it within aerospace organizations using methodologies based on Safety Management System (SMS) [4];
- the ICAO reorganization of global airspace to make it more efficient in the management of traffic and to accommodate an increasing volume of aircraft maintaining the same safety level [2];
- the issues raised by the so called ‘green aviation’ [5], that are related to the research for more efficient or innovative carbon-neutral propulsion technologies.

According to the Authors, on the basis of the above mentioned elements, the most interesting and concrete level of integration of RPAS systems with manned aircraft is the case of specific operations. In order to make this scenario real, the increase of RPASs range and endurance performances is fundamental. This paper is on the evaluation of hydrogen fuel cells as a mean to enhance RPAS systems performances in terms of reachable range and endurance to perform specific risk category operations and integrate them into controlled airspaces operatively and safely.

This article is structured as follows: Section 2 focuses on fuel cells; after introducing some generic references to ‘green aviation’ and hybrid propulsion technologies, fuel cell principle of operation is described. Section 3 describes the main steps to size a fuel cell system to feed electrical motors of a fixed wing RPAS capable of specific operations category; then, a parametric model of a fuel cell power line based on operative and safety requirements for medium range/medium endurance RPAS is shown. Section 4 contains a discussion of the possible future development of the present study. Finally, Section 5 sums up the conclusions related to the topics presented in this article.

2 Hydrogen Fuel Cells

Green aviation is a trend diffusing in aeronautics according to the new sensitivity on environment concerns. Green aviation studies the impact of aviation on the environment, considering carbon and NOx emissions, and noise [5]. Green aviation can be intended both from the side of air segment of aviation, that is aircraft [6], and from the side of ground segment of aviation, that is airports and their ground facilities: e.g. auxiliary power units (APUs) to feed airplanes on ground before a flight [7].

Green aviation comprehends investigations on hybrid propulsions systems [8] as well as on renewable source of energy theoretically capable, among other advantages, to provide good results in terms of aircraft endurance, range, and optimization of fuel consumption. The fuel cells [8] are electrochemical devices that convert the energy of a fuel (such as hydrogen, natural gas or other hydrocarbon-based fuels) directly into electricity. So, the principle of operation is the same as for traditional cells, but fuel cells use external source of energy to generate electricity. Fuel cells devices are composed of an electrolyte layer in contact with an anode on one side and with a cathode on the either side. The chemical reaction at the base of the operation of a fuel cell is an electrolysis reaction. More in detail, a chemical reaction of oxidation occurs on the anode side of the fuel cell, while a reduction is performed on the cathode side.

There is a variety of fuel cells available on the market. In this paper attention will be focused on Polymer Electrolyte Membrane or Proton Exchange Membrane Fuel Cell (PEM-FC) technology [8], due to their low working temperature (between -25°C and 75°C [9]) and to the very interesting properties of the polymer that composes the cell membrane. This technology was discovered in the 1960s, and over the decades and the applications (from powering a cellular mobile to a train locomotive) has confirmed its simplicity of use and quick start-up. The above mentioned polymer membrane is characterized by a particular behavior: it is impermeable to gas but it allows the passage of protons (hence the name ‘Proton Exchange Membrane’ also known with its commercial name Nafion®, made by DuPont company).

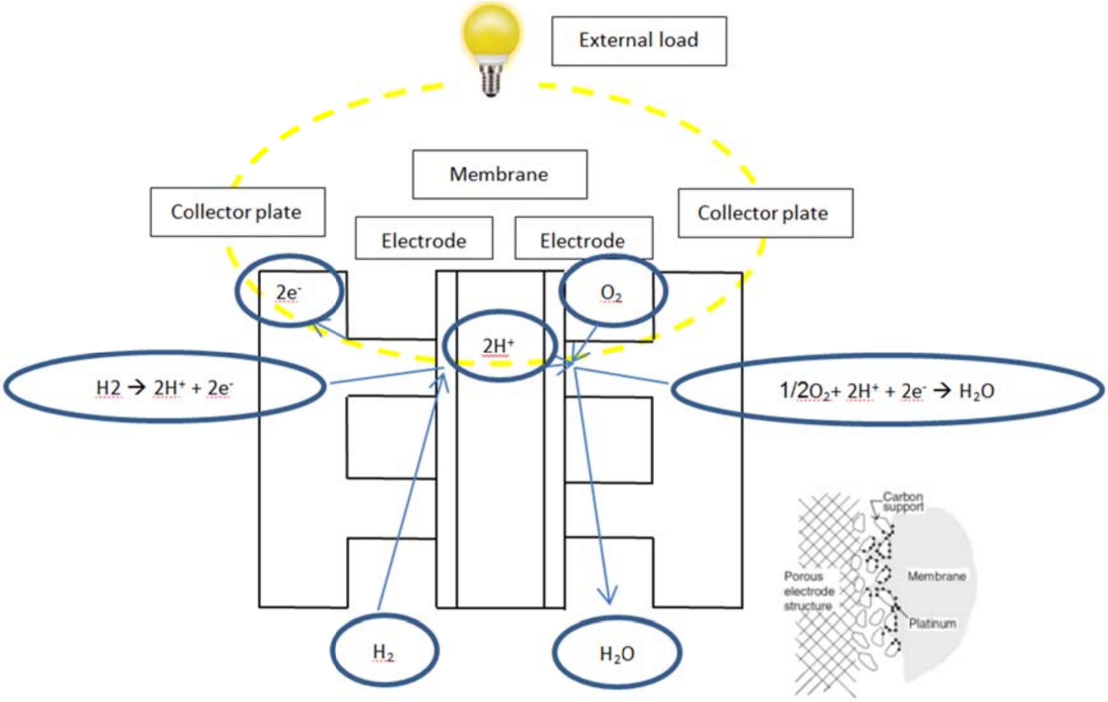

Fig. 1: The basic principle of operation of a PEM fuel cell [8]

Such membrane acts as the electrolyte; it is squeezed between the two porous conductive electrodes. The electrodes are made out of carbon cloth or carbon fiber paper. At the interface with the polymer membrane, the electrodes are upholstered with catalyst particles of platinum (i.e. the most common case), as shown in Fig. 1 [8].

Electrochemical reactions of interest occur at the surface of the catalyst at the interface between the electrolyte and the membrane. Hydrogen, fed on one side of the membrane, splits into its primary constituents, protons and electrons. The protons go through the membrane. The electrons travel through the electrically conductive electrodes; they cross the collectors, and enter the outside circuit where they perform useful work. Then they continue returning to the other side of the membrane.

On the catalyst sites of the membrane towards the other electrode they meet with the protons that went through the membrane and oxygen that is fed on the other side of the membrane generating water by mean of an electrochemical reaction. Finally they are pushed out of the cell with an excess flow of oxygen. A flow of direct electrical current results as final product of the described process [8]; this process is graphically shown in Fig. 1.

The side with the hydrogen is negative and corresponds to the anode; the side with the oxygen is positive and is the cathode. The above described basic chemical reactions that occur within a fuel cell are each one detailed hereinafter [8].

The anodic chemical reaction (hydrogen side) is:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

The cathodic chemical reaction (oxygen side) is the following:

$$½\, O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

The overall chemical reaction is the following:

$$H_2 + ½\, O_2 \rightarrow H_2O \quad (3)$$

The maximum amount of electrical energy generated by a fuel cell can be calculated, according to the Gibbs free energy formula, as [8]:

$$W_{el} = -\Delta G \quad (4)$$

The theoretical potential E of the fuel cell is:

$$E = -\Delta G/nF \quad (5)$$

where, ΔG is the free energy of the reaction (equal to 237,340 J mol^{-1}), n is the number of electrons involved (two, in this case) and F is the Faraday's constant (i.e. 96485 Coulombs/mol). The electrical potential of a fuel cell, at 1 atm of pressure and 25° C of temperature is E = 1,23 V. A value of electrical potential of this order of magnitude is typical of fuel cell; in other words a single cell usually generates very low potential differences and very low currents. For this reason single fuel cells are usually connected either in series, or in parallel, to form a stack, in such a way that several W to many kW of power can be generated.

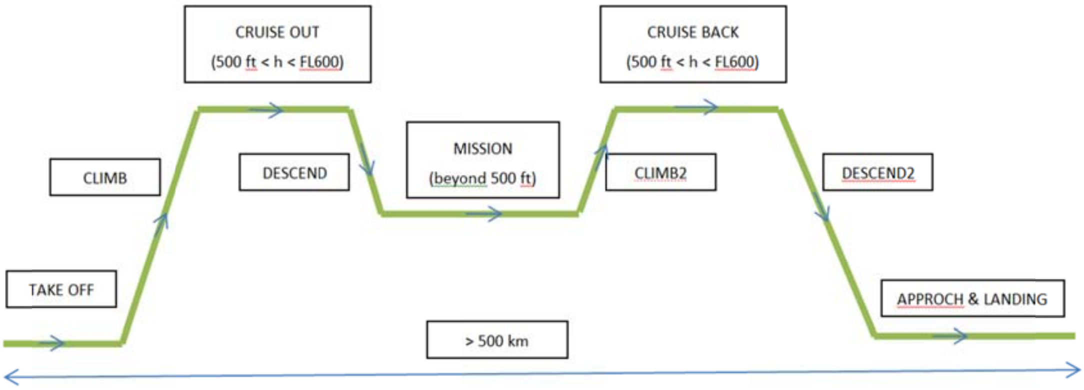

Fig. 2: Remotely Piloted Aircraft Systems (RPAS) mission profile [9]

The fuel cell stack requires other components to complete the system that are the fuel cell processing section called Balance-of-Plant (BoP), the power section (that is the component surrounding the stack itself), the power conditioning unit and the control unit. The fuel processing is required to produce a hydrogen-rich and possibly desulfurized gas. The power-conditioning unit converts variable DC to controlled AC current, with a specific frequency, active and reactive power; in addition, it acts as feedback to control the fuel flow to the stack [8].

3 Fuel Cell Power Line Model

The object of this paper is the description of a parametric model of a fuel cell power line based on operative and safety requirements for medium range/medium endurance RPAS systems. According to the authors, RPAS systems capable of this level of flight performance, can reasonably be able to perform specific risk category aerial sorties according to EASA/JARUS (Joint Authorities for Rulemaking on Unmanned Systems) RPAS concept of operations [1-3]. Before focusing on this topic, main steps to size a fuel cell system to feed electrical motors of a fixed wing RPAS is described. A fixed wing RPAS is supposed to be used because rotor wing RPAS usually fed, at the moment, by Lithium Polymer (LiPo) batteries only, cannot reach the desired performances. In order to calculate the necessary power for the considered RPAS, a possible realistic mission profile has been defined (as shown in Fig. 2 and according to [9]).

After take-off and climb the RPAS is required to navigate at its design cruise speed until descending towards the mission area where the payload will be operated. After the mission area, the flight profile foresees a second climb to come back to cruise altitude and cruise speed, until reaching the waypoint for the final descent, approach, and landing.

According to the UVS (Unmanned Aircraft Systems) categorization of RPAS a medium range RPAS is expected to fly over more than 500 km of range and for a period of time up to 10 ÷ 18 hours [9].

The architecture of the power line of the RPAS is schematically shown in Fig. 3 [10].

The fuel cell is the primary source of energy for the RPAS and it is fed by the hydrogen contained in the tank and by the oxygen contained in the air to generate electric current. The principle of working of the fuel cell has already been described in Section 2. The fuel cell and the LiPo battery are connected in parallel between them to the DC/DC transformer.

This equipment provides the correct potential difference to work to the RPAS loads through the DC power bus. The DC power bus is the component of the line able to select the source of power to use: the fuel cell is mainly used during the whole flight mission. The LiPo battery can be requested to work by the power bus in case of high demand of energy.

The DC power bus also has the function to protect the LiPo battery functionality avoiding extreme discharge cycles.

As widely described in [11], the main steps to size the power line in object are the following ones:

1. determination of the total energy associated to each phase of flight;
2. determination of the electrical power requested to the power line during each phase of flight;
3. energy allocation: the energy necessary to perform the flight operation shall be allocated between the fuel cell system and the LiPo battery;
4. determination of the necessary volume and mass of hydrogen of the fuel cell;
5. determination of the mass of the LiPo battery;

This methodology leads to more general considerations and to a more comprehensive parametric model to identify parameters and conditions necessary to make fuel cell a real option to integrate RPAS systems into controlled airspaces.

Two kinds of parameters can be identified: operational parameters and safety parameters.

Operational parameters are: RPAS weight, RPAS airspeed, its airframe shape including scaling factors and its aerodynamic efficiency; factor of utilization of the fuel cells with respect to the redundancy, the power line efficiency, function of the fuel cell efficiency and flight conditions (i.e. temperature, altitude, pressure,), logistics for hydrogen supply.

Safety parameters are related to the presence of LiPo battery as a redundant source of energy with respect to the fuel cell.

Considering RPAS weight parameter, as a first estimation, the power requested to the fuel cell van be assumed to be directly proportional to the weight of the RPAS for a given set of design performances. Even if considering the high efficiency of PEM fuel cell in converting chemical energy in electrical energy and the high energy content of hydrogen, due to the lowest density of hydrogen, large volumes of it can be requested. For aeronautical applications as well as for automotive ones, the common and consolidated practice is to store hydrogen at the gaseous state inside appropriate tanks at very low temperatures and high pressure to increase density. In the worst case, the weight of the fuel power system can affect RPAS flight attitude and performances. The best compromise shall be found among these parameters [12]:

- the quantity of hydrogen to be stored into the tank to perform mission profiles;
- the resulting dimensions of the tank; the volume size of the tank with respect to the space of the RPAS where it will be located;
- the total weight of the tank due to the greater thickness of its walls to contain the internal gas pressure.

For this reason, the sizing of the hydrogen tank is the most delicate phase when designing a fuel cell power line. As a general requirement, the best combination of pressure and volume of the hydrogen tank can be determined with regards to a global evaluation of RPAS flight performances [11].

RPAS airspeed and aerodynamic efficiency have an impact on the request of energy to the power line during the cruise phases that is during most of time of flight. Aerodynamic design solutions shall assure high values of efficiency and scale factors [13] that influence on the efficiency of the RPAS through different airframe dimensions shall be accurately chosen. For given desired values of flight range and endurance, efficiency influences consumption and sizing of the power line. The power line efficiency depends on the efficiency of the fuel cell and of the other components of the fuel cell system [8].

Temperature of the fuel cell shall be kept within a suitable range by mean of thermal management of the fuel cell [14]. Too high fuel cell temperatures would cause water evaporation and drying of the membranes. In this case, no hydrogen ion conduction though the membranes would be possible. Too low fuel cell temperatures would avoid water condensation inside the stack.

This condition would impede the gas diffusion and the transport of the reactants to the membranes.

In order to make RPAS fed by hydrogen fuel cells capable of regular specific operations in controlled airspaces, hydrogen fuel cells installed on board RPAS will need for refurbishment as it regularly happen for current aircraft with kerosene

Main concerns related to hydrogen logistics are about the transport of hydrogen and are due to its physical properties. As it happens for natural gas, hydrogen can be transported in liquid or gaseous state. Considering hydrogen at liquid state, it can be stated that the minor losses during transport and the higher volumetric storage density imply less frequent refill of stationery tanks with liquid hydrogen, even if energy is spent to liquefy it at temperatures of 21 K and at pressure of 1.3 MPa. Major concerns for supply of hydrogen at gaseous state are related to higher energy expenditures caused by very low density of hydrogen [15].

It must be noted that a redundant LiPo battery working in parallel to the fuel cell system enhances the safety of the power line, but in addition bring other benefits to the functionality and performance of the whole power line resulting in a lighter in weight [16] and more efficient and flexible technical solution (as proposed in [11] and [17]).

Due to the high power density of the battery with respect to the fuel cell, the LiPo battery easily provides the excess of power requested during the most demanding phases of flight remaining in stand by for the rest of the time. In fact, power requested during cruise is significantly lower than the peak power [17].

4 Conclusions

This paper deals with the possibility to apply Proton Electron Membrane (PEM) fuel cell as primary source of energy for a medium range/ medium endurance fixed wing RPAS in order to pose more realistic technical basis for their integration with manned aircraft into controlled airspaces. Main related operational and safety issues related to the design of hydrogen power lines able to provide such performances have been described.

Hydrogen propulsion can be the solution to make RPAS perform specific risk operations as defined by EASA into controlled airspaces.

New issues are raised in this paper, linked to:

- the safety risks caused by the flammability of hydrogen and the risk of explosion in presence of oxidizing gases;
- the need of more systematic studies about the power management system between the fuel cell and its redundancy and its dynamic response to demanding flight conditions into controlled airspaces;
- the implementation of a suitable network on ground to refurbish hydrogen for flight activity.

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