APACHE: Integrated Hybrid Fuel Cell System for 2-Seat All Electric Aircraft Propulsion

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APACHE: INTEGRATED HYBRID FUEL CELL SYSTEM FOR 2-SEAT ALL ELECTRIC AIRCRAFT PROPULSION

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Keywords: *aviation, PEMFC, Li-ion battery, hybridization, airworthiness*

Abstract

The French APACHE project aims at demonstrating the feasibility of using a Hybrid Fuel Cell System (HFCS) as the power generator for all electric 2-seat aircrafts. This study focuses on three main topics: airworthiness of Proton Exchange Membrane Fuel Cells (PEMFC), their hybridization with Lithium Ion (Li-Ion) batteries and systems' integration into light aircrafts. Altitude and inclination tests have been led and allow to conclude on the ability of PEMFC to operate in aeronautical conditions. A comparison of aerobic and anaerobic fuel cells is realised and reveals the superiority of anaerobic fuel cells for high altitude applications. Innovative architectures of hybridization are proposed and tested numerically and experimentally. Finally, examples of integration to two light aircrafts of a HFCS composed of an anaerobic FC, hydrogen and oxygen storages and a Li-Ion battery pack are presented.

1 Introduction

Recent developments in fuel cell technologies and improvements of its power generation capacity lead the industry to consider it as a serious alternative to internal combustion engines. As an evidence, Honda, Mercedes Benz, Toyota, Hyundai and more have produced commercially available fuel cell vehicles [1–4]. Several projects of fuel cell aircrafts intend to demonstrate the feasibility of using such electrochemical devices as electrical generators for clean aviation, as the ENFICA-FC project [5]. Fuel cell systems have many potential applications in aeronautics, as APU's (Auxiliary power Units) [6], emergency power generator [7], nose wheel energy drive [8] and light aircraft propulsion [5,9,10].

The French APACHE project (Application of Hybridized Loaded Fuel Cell), supported by the FUI French fund and PEGASE pole, aims at demonstrating the feasibility of using a Hybrid Fuel Cell System (HFCS) as the power generator for an all electric 2-seat aircraft. This ambitious and multi stakeholders project consists of three industrial partners (Helion, fuel cell system manufacturer, ECT Industries, on-board systems and equipments manufacturer, Eurocopter, helicopter manufacturer) and one public research laboratory (Centre for Energy and Processes, MINES ParisTech). The innovation carried by the APACHE project is to integrate an oxygen / hydrogen fuel cell device into a Choucas, a 14 m wingspan motor-glider. Using pure loaded oxygen as the electrochemical oxidant presents many advantages: a higher efficiency of the overall system compared to a air / hydrogen system, a higher cruising altitude and no risk of system contamination by air pollution [11]. The key objective of the APACHE project is to demonstrate the feasibility of propelling the Choucas thanks to a HFCS and an electric motor. To achieve this goal, studies are being carried out to investigate systems' integration, airworthiness of HFCS, and hybridization architectures.

2 Theory and numerical models

2.1 PEMFC

Proton Exchange Membrane Fuel Cells are electrochemical devices producing water, electricity and heat thanks to the cold combustion of hydrogen with oxygen. The two half-equations (1) and (2) and the overall reaction equation (3) are given hereafter:

$$H_2 \xrightarrow{catalyst} 2H^+ + 2e^- \quad (1)$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \xrightarrow{catalyst} H_2O \quad (2)$$

$$H_2 + \frac{1}{2}O_2 \xrightarrow{catalyst} H_2O \quad (3)$$

The main part of the PEMFC system is the stack, the assembly of elementary cells producing electricity. Each cell is composed of two bipolar plates and a Membrane Electrode Assembly (MEA) as shown on Fig. 1. The bipolar plates are made of graphite or coated metal. Bipolar plates ensure several functions : electrical connection between cells so that the voltage of the stack is the sum of the voltage of each cell, gas distribution and cooling fluid distribution.

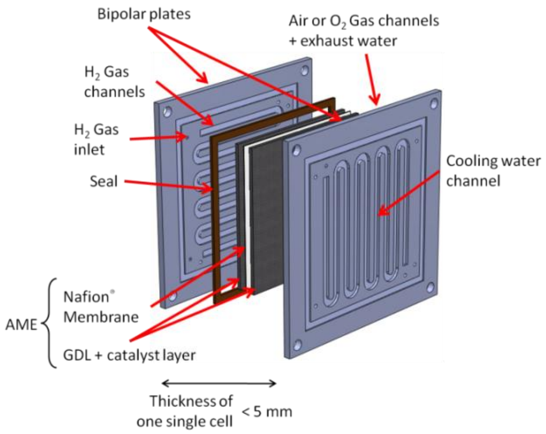

Fig. 1: Schematic of a single cell.

The MEA is composed of the Gas Diffusion Layer (GDL), the two electrodes (anode and cathode) and the membrane made of electrolytic polymer (usually Nafion® or other proton conductive materials).

The GDLs (conductive porous media such as carbon foam) ensure the diffusion of gases homogeneously, and support the catalyst layers. The catalyst layers are composed of a platinum powder and electrolytic polymer sprayed on the GDL carbon foam.

The working principle of a fuel cell is briefly described in Fig. 2.

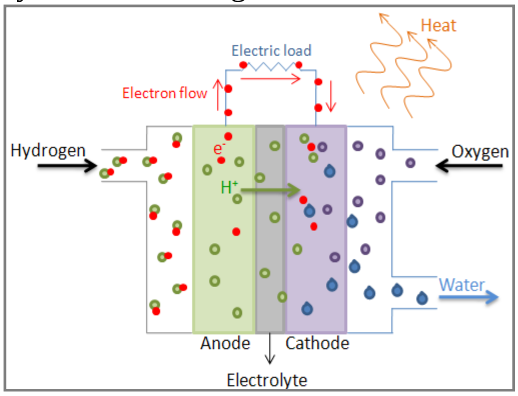

Fig. 2: Schematic of the working principle of a fuel cell.

The voltage of a fuel cell drops as the current increases. The theoretical open circuit voltage (OCV) of a fuel cell is 1.23 V, but it is closer to 1 V in practice. The nominal voltage of a single cell is around 0.7 - 0.6 V (maximum efficiency) and the minimal voltage is usually 0.5 V. A typical polarization curve is presented in Fig. 3.

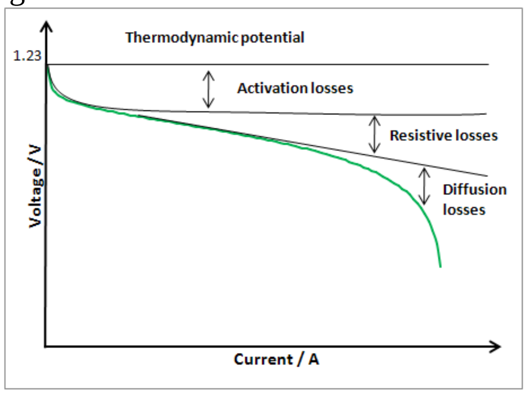

Fig. 3: Typical polarization curve of a single fuel cell.

The voltage response of a fuel cell can be modeled by a set of equations describing the OCV and the different losses [12–14], the cell voltage being the difference between the OCV and the losses, as presented in equation (4):

$$U_{cell} = E_{rev} - U_{act} - U_{ohm} - U_{diff} \quad (4)$$

The OCV is given by equation (5):

$$E_{rev} = \frac{-\Delta G}{2\mathfrak{F}} + \frac{\Delta S}{2\mathfrak{F}}(T_{FC} - T_{ref}) + \frac{RT_{FC}}{2\mathfrak{F}}\left[ln(P_{H_2}) + \frac{1}{2}ln(P_{O_2})\right] \quad (5)$$

The activation losses occurring at low current densities are described by equation (6):

$$\mathrm{U_{act}} = -[\zeta_1 + \zeta_2 \mathrm{T_{FC}} + \zeta_3 \mathrm{T_{FC}} \ln(\mathrm{I_{FC}}) + \zeta_4 \mathrm{T_{FC}} \ln(\mathrm{C_{O_2}})] \quad (6)$$

where $\mathrm{C_{O_2}}$ is a function of the oxygen partial pressure P_{O_2}. The resistive losses caused by the electrical resistance of the fuel cell is expressed by equation (7):

$$U_{ohm} = \mathrm{I_{FC}R_{ohm}} \quad (7)$$

Finally, the diffusion losses occurring at high current densities are given by equation (8):

$$\mathrm{U_{diff}} = -\mathrm{B}(\mathrm{P_{O_2}})^3 \ln\left(1 - \frac{\mathrm{J}}{\mathrm{J_{max}}}\right) \quad (8)$$

In order to use these equations and model a specific fuel cell, it is necessary to identify the parameters by fitting tem with experimental measurements, tanks to least square method.

As shown in the abovementioned equations (5, 6 and 8), the FC voltage is strongly dependent on the reactants partial pressure, more specifically on the oxygen partial pressure. Therefore, concerning aerobic FC systems (using ambient air as the oxidant), the drop in ambient pressure due to altitude triggers a drop of the voltage response which is necessary to quantify. Using pure oxygen (compressed and loaded in canister) as the oxidant is a serious option that has to be considered and compared to the use of ambient air.

Additionally, the sensitivity of PEMFC systems to inclinations has to be evaluated. The produced water that is evacuated through the cathode channels could trigger flooding and therefore malfunctioning if not correctly removed.

2.2 Li-Ion batteries

Li-ion batteries are electrochemical reversible devices widely acknowledged for their power density, no need of maintenance, reliability and long lifetime. The energy of Li-ion batteries is stored in the electrode materials. The central electrolyte ensures the transfer of ions, while two separators electrically isolate the electrodes and the electrolyte (Fig. 4). The electrons are transferred from an electrode to the other through an external electric circuit. The OCV of Li-ion cell is usually close to 4.2 V. The voltage of a Li-ion cell mainly depends on both the load current and the State of Charge (SoC). The voltage range of the cell depends on the chemical reactants used but is commonly from 4.2 V to 3 or 2.5 V. As the reactants are stored in the electrodes, the voltage response strongly depends on the electrochemical reaction kinetics and history. As a consequence, a representative numerical model of a Li-ion battery has to be time dependent.

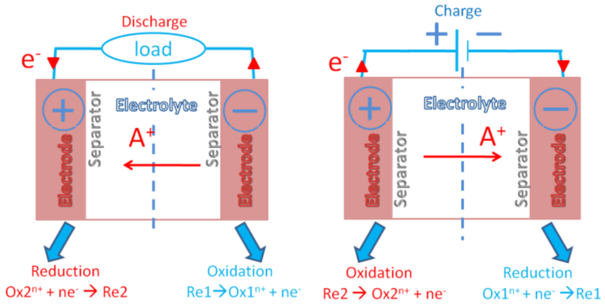

Fig. 4: Schematic of the working principle of a Li-ion battery.

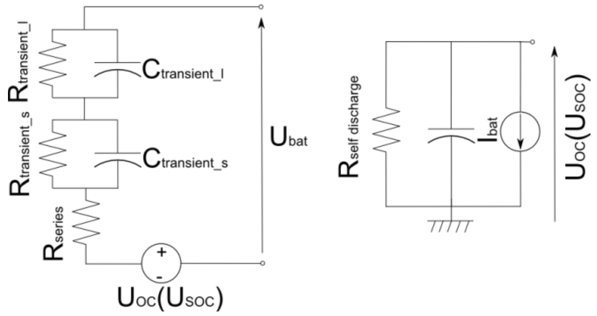

Fig. 5: Schematic of the Li-ion battery numerical model [15].

A commonly used numerical model [15] is presented on Fig. 5. The numerical model consists in two electrical circuits, the first one to model the voltage response and the second one to model the SoC by integrating the current demanded to the battery over the time. The capacity of the SoC model is the electric capacity of the battery. In the voltage response model, capacities, resistances and the voltage source depend on the SoC. In order to model the voltage response of a specific battery, it is necessary to fit the parameters with experimental measurements.

3 PEMFC airworthiness

3.1 Altitude sensitivity

Sensitivity of PEMFC performance to altitude is experimentally investigated. The voltage response of the system is expected to decrease as the ambient pressure drops down, as explained in section 2.1. A 1 kW, 24 cells, aerobic PEMFC system named Bahia and made by Helion (French FC manufacturer) is tested at five different air stoichiometric factors (from 1.5 to 2.5) and at three different altitudes (200 m, 1 200 m and 2 200 m) [14].

In a limited range, it is known that increasing the air stoichiometric factor increases the voltage response of the FC (too high stoichiometric factors can lead to membrane dehydration and proton conductivity decrease).

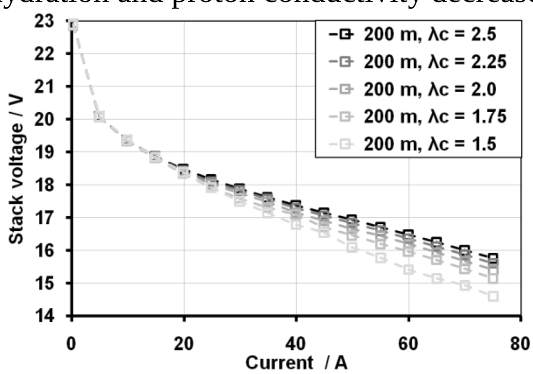

Fig. 6: Polarization curves at λ_c = 1.5, 1.75, 2.0, 2.25 and 2.5 and at 200 m.

As shown in Fig. 6, at 200 m, the voltage response can be enhanced by increasing the air stoichiometric factor from 1.5 to 2.5. However, an increase in air stoichiometric factor leads to higher compressor power consumption.

The tests conducted at higher altitudes revealed the same tendency, showing that best performances are obtained for an air stoichiometric factor of 2.5.

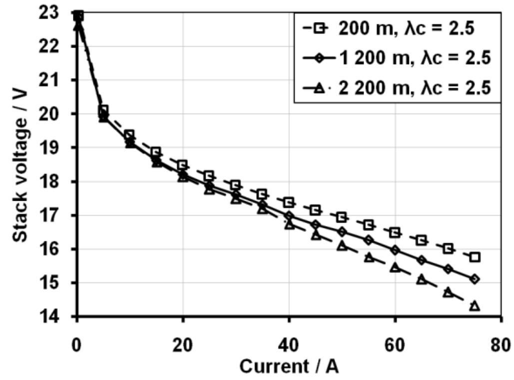

Fig. 7: Polarization curves at 200 m, 1 200 m and 2 200 m and at λ_c = 2.5.

As shown on Fig. 7, the voltage response of the FC stack decreases as the altitude increases. After deep analysis, it is found that the air compressor overpressure is also decreased as the altitude is increased. Therefore, three parameters are playing major roles in the oxygen partial pressure value: the ambient pressure, the compressor overpressure and the average oxygen molar fraction in the cathode channels (which depends on the air stoichiometric factor) as shown by equation (9):

$$P_{O_2} = \left(P_{amb} + \Delta P_{comp}\right)\overline{X_{O_2}} \qquad (9)$$

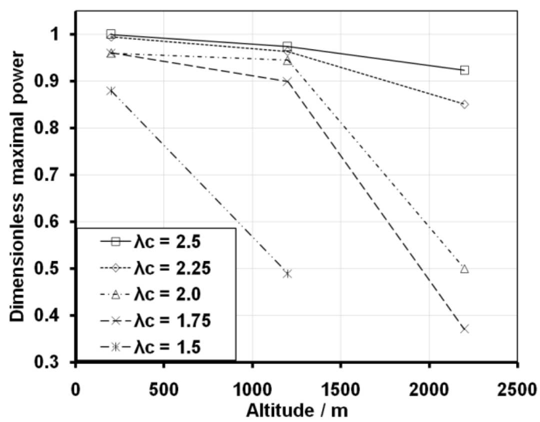

Fig. 8: Maximal FC stack output power as a function of altitude for different air stoichiometric factors.

A summary of all the experiments made at different altitudes and different air stoichiometric factors is given in terms of FC stack maximal output power in Fig. 8. It appears that for air stoichiometric factors higher than 2.25, the maximal power loss ranges from 8 to 15 %. At lower air stoichiometric factors (from 1.5 to 2.0), a drastic drop in maximal output power is observed (50 to 65 %). This drop in output power is mainly due to a drastic decrease in oxygen partial pressure.

As a consequence, it appears that PEMFC systems are relevant for ground applications (nose wheel electric drive), low altitude applications, as APU replacement or for low altitude light airplane propulsion. Concerning applications at higher altitude, it appears necessary to evaluate the power loss of the FC stack. Experimental investigations at altitudes higher than 2 500 m are logistically difficult. Therefore, the model presented in section 2.1 is first fitted with the experimental data obtained at 200 m, 1 200 m and 2 200 m and secondly employed to extrapolate the voltage response of the FC stack at 5 000 m.

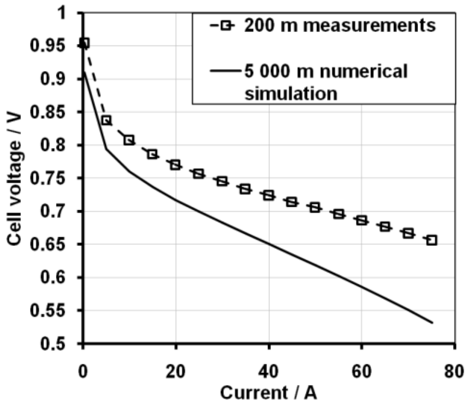

Fig. 9: Comparison of cell voltage measurements at 200 m and cell voltage numerical simulation at 5 000 m (λ_c = 2.5).

The results presented in Fig. 9 reveal a drastic drop of cell voltage response at 5 000 m. The voltage response at maximal current is reduced of 19 % and its value is close to 0.5 V, which is the low cell voltage limit determining the maximum operable current. Therefore, in addition to the drastic loss of output power, membrane dehydration phenomena and diminution of the maximal current (not considered in the model) could occur and decrease even more the output power of the FC stack. As a consequence, it appears necessary to consider specific developments for the cathode reactant supply.

In order to enhance the functioning of the FC system at high altitude, it would be necessary to integrate an air compressor responding to the specific needs of aerial applications. A centrifugal compressor offering a pressure ratio greater than 2 would compensate for the pressure decrease due to altitude. This kind of compressors need further developments in order to fulfill the requirements of mass and volume. Research is led in this area [16], so we decided to concentrate our effort on the alternative of using pure loaded oxygen as the oxidant. This solution was first used decades ago for spatial applications.

The comparison is made between an aerobic PEMFC system (based on Bahia system properties) comprising an air compressor matching the DoE specification targets for 2010 and an anaerobic PEMFC system (based on IMHOTEP system, developed by Helion for the APACHE project) plus a pure oxygen tank. For both systems, hydrogen storages at 350 bar and 700 bar have been considered. A nominal usable power of 20 kW at cruising altitude was the main specification. Results for cruise at 5 000 m are reported in Fig. 10. The comparison was made for 1 000 m, 2 500 m and 5 000 m, for both mass and volume.

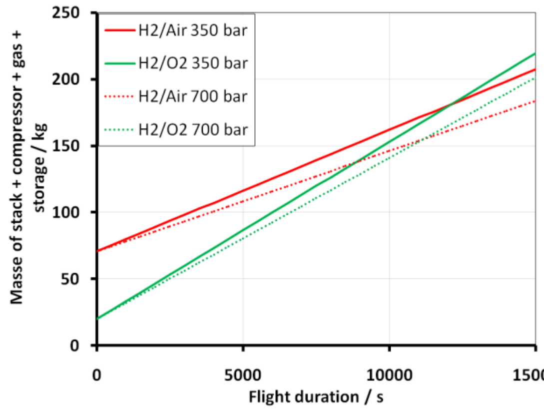

Fig. 10: Mass comparison for aerobic and anaerobic PEMFC, with respect to the duration of the flight, at 5 000 m.

The anaerobic system appears to be lighter than the aerobic system for short flights, even at 1 000 m (7 500 s). As the flight duration increases, the aerobic system becomes the lightest as it only requires to load hydrogen. But as cruising altitude increases, the flight duration over which the anaerobic system is the lightest increases (up to 11 000 s at 5 000 m). For the systems volume, the competition is tighter: anaerobic is the least voluminous up to 3 000 s at 1 000 m, and up to 4 000 s at 5 000 m.

The main difference between aerobic and anaerobic PEMFCs that plays a major role in the abovementioned comparison is the gas partial pressure. Indeed, the anaerobic system works with pure gases at a pressure of 2 bar. As a consequence, the maximal current density for anaerobic FC is 1.5 $A.cm^{-2}$, versus 0.8 $A.cm^{-2}$ for aerobic FC. The power density is directly affected in the same way: 1.1 $W.cm^{-2}$ for anaerobic FC versus 0.5 $W.cm^{-2}$ for aerobic FC. Therefore, anaerobic PEMFC systems are competitive with aerobic ones and to be seriously considered for aerial applications. Moreover, anaerobic PEMFC systems offer advantages compared to aerobic ones, as no sensitivity to air pollution (COx, NOx, ashes, salty fogs), increased reliability thanks to fewer auxiliaries (no compressor, no gas humidifier) and a faster response time (no inertia due to air compressor).

3.2 Inclination sensitivity

Inclination sensitivity test have been performed on working PEMFC systems (aerobic and anaerobic (Fig. 11)). Measurements include polarization curves and static nominal power tests under various inclinations (along the two axes) representative of in flight operation. Each measurement has been repeated at least twice in order to attest for repeatability. No significant output power loss were measured neither for the aerobic nor for the anaerobic PEMFC. Water balance was performed for the anaerobic system showing no significant differences and thus leading to the conclusion that inclined operation do not constitute any difficulty for PEMFC systems.

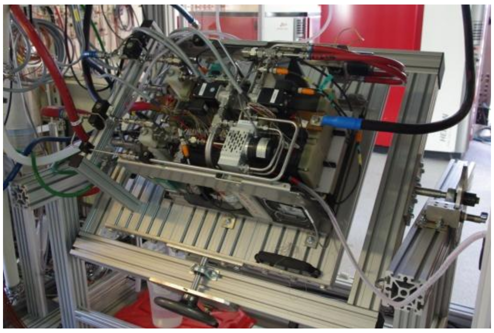

Fig. 11: Picture of the IMHOTEP system in inclination.

4 PEMFC hybridization with Lithium Ion batteries

Hybridization of FC systems with secondary power sources has already been studied and acknowledged. For automotive applications, the main advantage is to increase the response time to power peaks and to enable power recovery. In the present case, hybridization of PEMFC system with Li-ion batteries is considered for sizing reasons. The power profile of a flight is quite constant except during take-off. The peak power needed during the take-off phase is approximately twice the power needed for level flight. This peak power is requested only during take-off and initial climb, that is 10 minutes in the present specifications. For such a short duration, it is not relevant to size the FC (and its auxiliaries) considering the maximal power needed. As FC systems offer very good energy densities and Li-ion batteries offer good power densities, it is interesting to take benefit of both technologies by hybridizing them together. In the present study the power needed for level flight is 20 kW and the power needed during take-off is 40 kW. We thus opted for a 20 kW PEMFC system and a 20 kW Li-ion battery pack. In the next section, the hybridization architecture of both power sources is studied. We propose an innovative method, the direct hybridization and we compare it to the indirect hybridization.

4.1 Indirect hybridization

The indirect hybridization consists in connecting in parallel the FC and the Li-ion batteries through a DC/DC converter. Thanks to this method, it is possible to control each power source separately. In this manner, the distribution of the load on each source can be optimized to enhance the overall system's efficiency or to adapt the power management to various strategies. Indirect hybridization requires a DC/DC converter which is a heavy item and it also requires a control unit that imposes the power distribution. Furthermore, both the converter and the control unit are additional items and therefore sources of potential failure. As indirect hybridization is a commonly employed method [17,18], it is not further developed in this article.

4.2 Direct hybridization

The indirect hybridization consists in connecting the FC and the Li-ion batteries in parallel directly, with no electrical conversion in-between. This technique implies that the voltage of both power sources is equal at anytime. The current distribution between the FC and Li-ion battery is "naturally" settled to respond to the load demand. The direct hybridization requests a precise sizing of the elements in order to respect the voltage equality, to avoid back currents to the FC and to respond to the load demand properly. The first constraint is that voltage relative variations of both sources must be of the same order. The FC voltage usually ranges from 1 V (OCV) to 0.5 V (minimum cell voltage). Li-ion batteries usually have an OCV of 4.2 V, meaning that the minimum Li-ion cell voltage should be around 2.1 V to match our specifications. The best Li-ion technology is therefore the so called Spinel Li-ion battery, made of $LiMn_2O_4$, that has a minimum cell voltage of 2.5 V. Spinel batteries are also characterized by a I-U curve slope compatible with direct FC hybridization.

In order to investigate the feasibility of direct hybridization before realizing a reduced scale experimental test bench, a numerical model was developed. This numerical model is based on the previously presented FC and battery models. The battery model is fitted with experimental measurements made on a 10.5 Ah Li-ion battery and validated by comparison to measurements of various discharge cycles. The two fitted models (FC and Li-ion battery) are then introduced in the hybridization model. In this manner, it is possible to determine precisely the ideal proportion of Li-ion cells and fuel cells to be hybridized together and what power profile can be imposed to the hybrid system.

In the present study, the HFCS considered was scaled down to $1/22^{th}$ of the APACHE project, that is 1.82 kW. It is composed of the 1 kW 24 cells Bahia FC previously presented. The parameter to determine is mainly the number of Li-ion cells to hybridize. Ideally, the number of fuel cells should be settled as a function of the number of Li-ion cells, as this would allow a more precise adjustment of the HFCS voltage (that should be as close as possible to a multiple of 4.2). In our case, only the 24 cell Bahia FC was experimentally available in our laboratory.

The Fig. 13 presents the results of the HFCS numerical model considering 24 cells FC system and 5 Li-ion cells. The figure presents the HFCS response to a load profile based on the real flight power profile that was specified in the APACHE project. This power profile is composed of six phases: take-off, initial climb, normal climb, cruise, descend and landing. The power demand and power of each source is presented on the first graph. The second grah presents the current of the HFCS and the current of each source. The third graph presents the voltage of both sources. Finally the fourth graph presents the SoC of the battery pack.

The power produced by the HFCS responds exactly to the load. During the take-off, the power distribution between the two sources is not exactly 50 % - 50 %. During the cruise, the Li-ion batteries participate to the power generation until its SoC is too low. This power repartition is different from the one that was envisaged for the indirect hybridization. Indeed, in the indirect hybridization , during the cruise, only the FC is generating power. After the landing, the power demand is zero. At this point, the FC and the Li-ion batteries still have the same voltage and the current produced by the FC charges the Li-ion batteries and the SoC increases.

The direct hybridization concept proposed here appears as an interesting option. Nevertheless, the electric architecture needs further optimization in order to be operable in aeronautical applications. The numerical simulation tests performed are very promising and experimental validation is being carried out at the time this article is written.

5 HFCS integration and security

The integration of the overall hybridized system into the Choucas (motor-glider) is studied in this section. Some good sense principles should be the basis for HFCS integration. As an example, the FC system and battery pack should be placed as close as possible to the electric motor, in order to reduce the resistive losses and the weight due to cables.

The H_2 and O_2 gas reservoirs should not be placed too close to each other. Ideally, gas reservoirs should be separated and located in two different and not communicating enclosures (Fig. 12). This precaution is taken to avoid inflammable or explosive mixes as much as possible. Furthermore, each gas enclosure should be naturally ventilated in order to avoid the accumulation of a leaking gas. To do so, air inlets and outlets smartly positioned can be sufficient. The Choucas is an interesting example concerning the gas storage integration. Indeed, its wing thickness allows to receive a gas reservoir. If possible, the gas pipes from the gas storage to the FC should be fixed on the outer side of the fuselage for safety reasons.

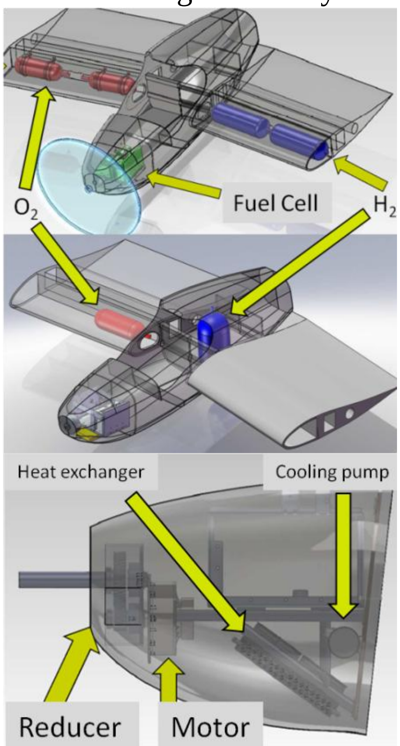

Fig. 12: Schematics of the PEMFC system, gas storage and electric motor possible integrations.

The study of the HFCS integration to the Choucas also comprises a mass balance of the airplane (Table 1). As presented in the mass balance, it is technically feasible to integrate all the elements while respecting the MTOW (Maximum Take Off Weight) of the Choucas. However, the mass repartition in the airplane slightly changes in comparison with the thermal version. Indeed, the integration of gas storage in the wings involves a structural analysis in order to determine if the spars are resistant enough. In the presented possible integrations, the aircraft balance has been considered and respected.

From an integration point of view, the feasibility has been demonstrated, even though the study should be completed with the spars resistance analysis. No major technical difficulty were raised that would prevent HFCS integration.

Max mass (MTOW)	536
Empty mass	265
Gains over taken out material	-64
Empty mass without engine	201
Difference (MTOW-mass w/out engine)	335
FC System	75
Battery mass	40
Engine + Dimmer mass	19
Reservoirs' mass	115
Pilot's mass	86
Total	536

Table 1: Mass balance of the Choucas equied with a HFCS comprising a 20 kW H_2 / O_2 PEMFC and a 20 kW Li-ion battery pack.

6 Conclusion

The present study demonstrated the feasibility of using HFCS as power generators for light aviation. In particular, the focus was made on the sensitivity to altitude and inclinations and on the hybridization of the FC system with Li-ion batteries. The example of the Choucas has been given for the integration, mass and volume study.

The altitude sensitivity study shows that aerobic PEMFC are adapted for altitudes up to approximately 2 500 m. For higher altitude applications, it appears necessary to further develop the air compressor technology. Studies are being led in this field. For high altitude applications, the anaerobic PEMFC is a promising solution. Thanks to much higher current densities, the performances of anaerobic PEMFC are approximately twice those of aerobic ones. However, pure oxygen needs to be loaded onboard. Nevertheless, the anaerobic system appears to be lighter than the aerobic one.

Sensitivity to inclination has been experimentally investigated and no significant loss of performance was measured. This result is encouraging.

Hybridization of PEMFC with a secondary power source appears as the best option for the application of light aircraft propulsion. Besides the increased security thanks to the use of two power sources, hybridization allows to take advantage of both the power density of batteries and energy density of PEMFC in order to reduce the overall system mass and volume. The architecture of hybridization remains an open topic as many possibilities exist. Depending on the application and on the precise power demand profile, it is possible to offer very interesting solutions.

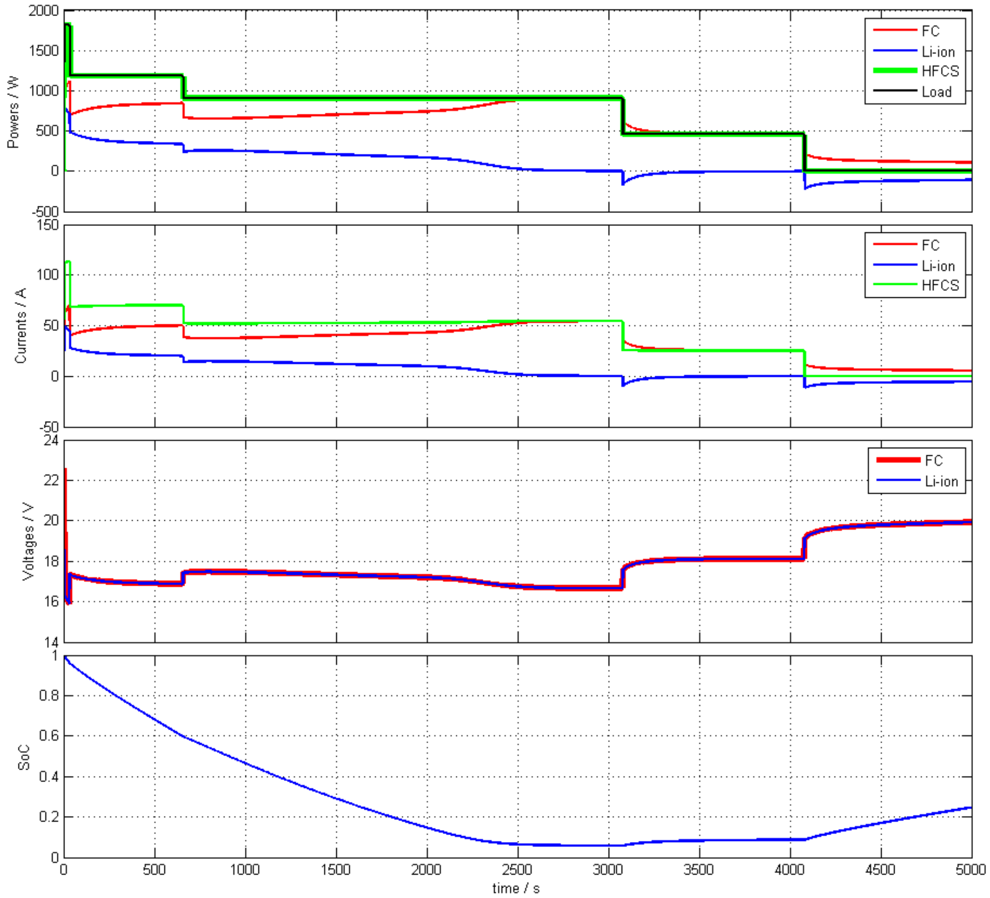

Fig. 13: HFCS response to flight profile load (Powers, currents, voltages and SoC).

The integration of HFCS to light aircraft still raises several questions, such as mass, volume and security. The continuous improvements on the power and energy densities of FC and batteries are promising. Concerning the security, the development of experimental demonstrations is a necessary first step. In this manner, return on experiment will help determining the potential lacks.

Finally, the APACHE project aimed at demonstrating in flight the Choucas powered by a HFCS. This project was founded for three years and extended for one additional year. Many difficulties, other than scientific or technical, have raised. The unexpected spar resistance analysis that was required by the DGAC (French agency for safety of aviation) represented a too expensive cost and time demanding task.

7 Letters and symbols

U	Voltage
I	Current
J	Current density
ΔG	Free Gibbs energy of reaction
ΔS	Entropy of reaction
$\mathfrak{F}$	Faraday's constant
T	Temperature
R	Perfect gasses constant
R	Resistance of battery or FC
P_{H_2}	Hydrogen partial pressure
P_{O_2}	Oxygen partial pressure
ζ_i	FC model parameters
R_{cont}	Contact resistance
R_{mem}	Membrane resistance
B	FC model parameter
λ_c	Cathode stoichiometric factor

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9 Acknowledgement

The authors are grateful to the APACHE project partners and to the technician team for the precious help given during experiments.

10 Copyright issues

11 Copyright Statement