

A Fuel Cell Based Propulsion System for General Aviation Aircraft: The ENFICA-FC Experience

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ABSTRACT

The hydrogen and fuel cell power based technologies that are rapidly emerging can be exploited to start a new generation of propulsion systems for light aircraft and small commuter aircraft.

Different studies were undertaken in recent years on fuel cells in aeronautics. Boeing Research & Technology Centre (Madrid) successfully flew its converted Super Dimona in 2008 relying on a fuel cell based system. DLR flew in July 2009 with the motor-glider Antares powered by fuel cells.

The goal of the ENFICA-FC project (ENvironmentally Friendly Inter City Aircraft powered by Fuel Cells - European Commission funded project coordinated by Prof. Giulio Romeo) was to develop and validate new concepts of fuel cell based power systems for more/all electric aircrafts belonging to a "inter-city" segment of the market. As a result of the project, a technology demonstrator was designed, manufactured and tested: a new proton exchange membrane (PEM) fuel cell based power system was installed in the Skyleader RAPID200 that had its demonstrative flights in 2010.

One of the most critical, if not the most critical, aspect of the all-electric power system adopted for demonstrator is undoubtedly prediction of fuel cell behaviour, specifically in terms of temperature control since reduced volumes and low weights (needed for the aeronautical applications) are not beneficial from a heat-management point of view. Moreover temperature control of PEM fuel cell is extremely important for a correct employment of the cell itself and, since the fuel cell is the main power generating device on the aircraft (batteries are however present as emergency back-up), temperature control becomes a very important safety issue

too. In particular, as the ionic conduction of the polymeric membrane is a function of its degree of humidification, the stack temperature has to be carefully controlled to avoid phenomena of water evaporation causing an increase of ohmic drop and a decrease of stack performances. The output power of the fuel cells system is affected considerably by the change of the stack temperature.

The paper will report a description of the research activity that lead to the fuel cell based power system developed for the ENFICA-FC project: the main topics will regard the design phase, including numerical and theoretical modelling (validated by flight tests) of the fuel cell system and its cooling, the results of ground testing and installation and, finally, the results of flight testing.

INTRODUCTION

Rapidly emerging hydrogen and fuel cell power based technologies can now be exploited to initiate a new era of propulsion systems for light aircraft and small commuter aircraft. These technologies can also be developed for the future replacement of on-board electrical systems in larger 'more-electric' or 'all-electric' aircraft.

In February and March 2008, the Boeing Company (Lapeña-Rey, Mosquera, Bataller, & Ortí, 2010) successfully performed flight tests on the first manned fuel-cell motor-glider in aviation history. The fuel-cell demonstrator aeroplane was a modified two-seater motor glider equipped with a hybrid power source powering an electric motor that drove a variable-pitch propeller.

In July 2009, a German motor glider became the first piloted aircraft to take off under only fuel-cell power (DLR, 2009). The Antares DLR-H2, developed by the German Aerospace Center (DLR), took off from Hamburg Airport. This glider is



Figure 1. Converted Rapid200

a hydrogen-powered variant of the Antares 20E electric motor glider and has a 66-foot wingspan. The plane achieved 105 mph.

The EC funded project ENFICA-FC (ENvironmentally Friendly Inter City Aircraft powered by Fuel Cells) (Romeo, Borello, Cestino, Moraglio, & Novarese, 2007 b) (Romeo & Borello, 2010) (Romeo, Borello, & Correa, 2011 b) (Romeo, Cestino, Borello, & Correa, 2011 a) has the aim of obtaining a better understanding of the problems related to fuel cells applied in aeronautics. The main objective of the ENFICA-FC project was to develop and validate the use of a fuel cell-based power system for the propulsion of several more/all electric aircraft. The fuel cell system was installed on the light RAPID 200 sports aircraft (Fig.1), the first aeroplane (FAI Sporting Code Category C) to fly and be performance tested. Six test flights were successfully carried out by the Politecnico di Torino. The allelectrical power system was successfully tested during experimental flights in May-June 2010.

A new speed world record was established during several flights (Romeo & Borello, 2010) (Romeo, Borello, & Correa, 2011 b). The positive handling qualities and satisfactory engine performances of these six flight tests led the team to consider these successful flights as a good starting point for further long endurance high speed flights.

One of the most critical, if not the most critical, aspects of the all-electric power system adopted as the demonstrator is undoubtedly cooling; the reduced volumes and low weights that are needed for aeronautical applications are not beneficial from a heat-management point of view and hence cooling design and prediction becomes a challenging key activity for the whole flight test campaign.

Moreover temperature control of PEM fuel cell is extremely important for a correct employment of the cell itself and,

since the fuel cell is the main power generating device on the aircraft (batteries are however present as emergency back-up), temperature control becomes a very important safety issue too.

As briefly reported in the following section, final layout design sees all of the heat producing power plant's elements positioned in the engine-bay area; engine cowl was designed in order to guarantee an appropriate mass flow rate, keeping in account propeller effect and on the basis of specifications and experimental test results of the different system designers (power electronics, engine, fuel cells).

POWER SYSTEM DESCRIPTION

This section presents a brief overview of the RAPID200FC fuel cell sub-system as well as the designed engine cowl.

The whole power system consists of (Fig. 2):

- A fuel cell system producing about 20-22kW;
- Batteries that develop about 20kW during take-off and climbing and that are designed for emergency back-up;
- A DC/DC converter system that manages fuel cell and batteries;
- A DC/AC inverter that drives the electric motor;
- An Aircraft Power Management Unit and Distribution;
- A 43 kW electric brushless motor.

Electric motor and power electronics are both equipped with an air cooling system, while fuel cell relies on a water cooling system.

Table 1. Converted Aircraft Mass Breakdown

Component	Mass [kg]
Empty Aircraft [EA]*	221
Electro-Chemical Sub-System [ECSS]	103
Water Management Sub-System [WMSS]	
Heat Exchanger [HEXX]	
Control Sub-System [CtrlSS]	
Pressurized Hydrogen Sub System [H2SS]	51
Electric Motor [EM]	38
AC/DC+DC/DC Sub-System [ALDD]	14
Battery Pack 1 [BP1]	26
Battery Pack 2 [BP2]	26
Pilot [Pil]**	75
TOTAL	554
*Aircraft operative empty weight minus engine weight. The estimated weight includes a modified engine mount (3 kg) and the new propeller (4 kg).	
**The ENFICA-FC converted Rapid200 is designed for a single pilot.	

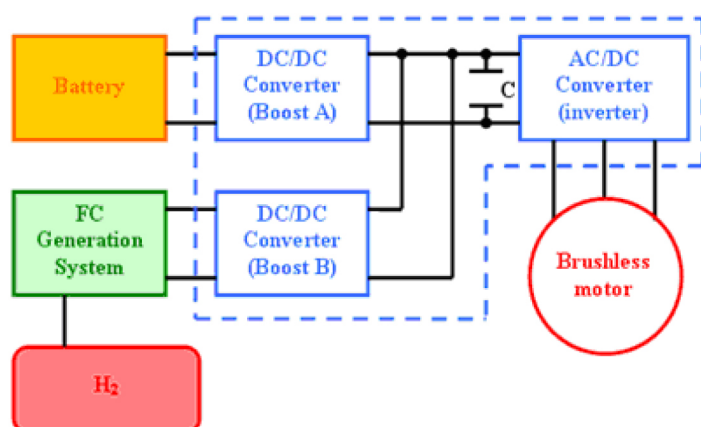


Figure 2. Power system schematic.

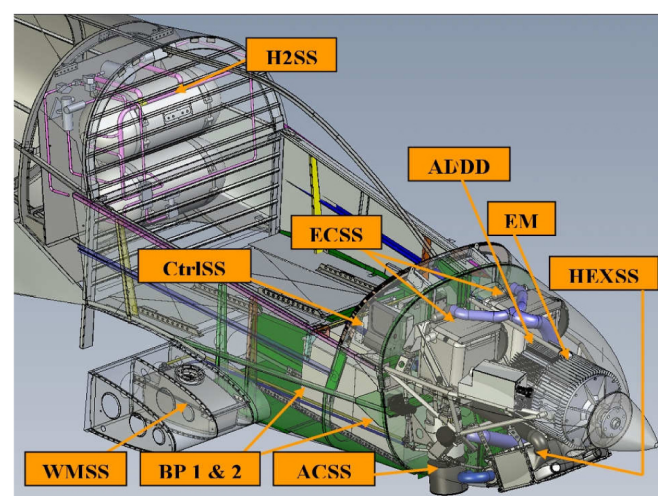


Figure 3. Final configuration of lay-out of internal systems (BP: Battery Pack, EM: Electric Motor, H2SS: Hydrogen Sub System, refer to text for the other acronyms).

Fig. 3 shows the final configuration of lay-out of internal systems, this lay-out is the result of different requirements concerning safety, functionality, balancing, weight saving and volumes constraints; all of the fuel cell sub-system's items are contained in engine bay, with the exception of water tank. A breakdown of masses related to the final flying prototype is reported in Table 1.

The fuel cell system (developed by IE), that is able to provide 20 kW on net unregulated power, consists of:

- Fuel Cell Stack & Electrochemical System
- Heat Exchanger System
- Air Delivery & Water recovery system
- Water Management Subsystem
- Electrical & Electronic Support System & Control and Internal Battery Subsystem.

An overview of the overall FC system is shown in Fig. 4.

The Electro-Chemical Sub System consists of two separate fuel cell units. To ensure a safe mounting system, the fuel cell stack is enclosed in a lightweight structure that provides forced ventilation of any hydrogen leak and electrical isolation. Stacks are designed for a maximum current of 110A.

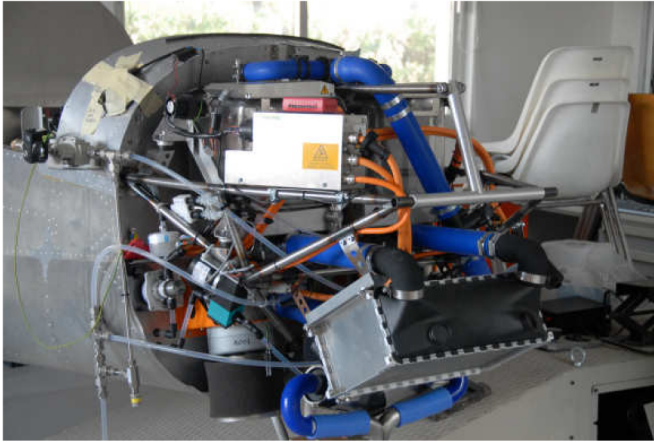


Figure 4. Fuel cell system assembled in the mock-up fuselage used for laboratory testing

Air Compressors Sub System [ACSS]: it is designed as two-stage centrifugal compressors in series. It brings fresh air from engine cowl inlet and feeds fuel cell stack with compressed air. The installed compressor is shown in [Fig. 5](#).



Figure 5. First and second stage compressor.

Heat Exchanger Sub System [HEXSS]: it is situated in the front part of the engine bay under the electric motor. The fresh air flows through the engine cowl inlet and heat exchanger matrix, cools the waste water-air mixture from fuel cell stacks and leaves the engine bay through the outlet opening around the front gear housing. Cooled waste water-air mixture comes to the cyclone where water is separated from the air and directed back to the water tank to be re-used. HEXSS is shown in [Fig. 6](#).



Figure 6. Installed heat exchanger and cyclone unit.

Water Management Sub System [WMSS]: it consists of water tank assembly situated in the right central wing part leading edge (original position of fuel tanks) and water pump, filter and flow meter situated in the engine bay. In [Fig. 7](#) the first prototype of the water tank is shown. The actual tank can't be shown because it's directly integrated in the wing leading edge aluminum sheet.



Figure 7. Water tank prototype.

Control Sub System [CtrlSS]: It comprises of FCS central communication and control module and Internal Battery Sub System (a battery that is used to start-up the fuel cell).

The air supply system and fuel cell stack venting system is studied with the CFD model presented in ([C. E. Romeo G. 2011](#)) where possible configurations for the ENFICA-FC new engine cowl are investigated. The final cowl configuration is shown in [Fig. 8](#) and used during flight tests described in following sections.



Figure 7. Final Cowl configuration

The FC stack and the hydrogen storage system are considered as self-standing systems. The fuel cell balance of plant represents the air delivery, hydrogen delivery, regulation and water cooling. Fuel cell water cooling is guaranteed through an heat exchanger (HEX) that receives the necessary flow rate and pressure drop from a main intake (SHEX) of about 0,042 m² positioned in the frontal part of the engine cowl. The air sent to the stack through a compressor is collected from a circular opening realized in the lower part of the engine cowl. The cowl air outlet can modify the local pressure distribution that in turn can modify the incoming flow behaviour. An example of this type of analysis with a preliminary exit area of about 0.18m² is included in (C. E. Romeo G. 2011) where the exit flow effect has been studied and a small influence on pressure coefficient (CP), locally confined in the proximity of the exit area, has been found.

DESIGN OF THE COOLING SYSTEM

OPTIMAL PROPELLER

Design of the propeller had a very important role in the development of RAPID200FC for two different reasons: the first one is the lower (if compared to a internal combustion engine) level of available power and the different operative condition (low speeds and low RPMs); the second one is the propeller effect on thermal management of the power system. The first point leads to the need of an optimized propeller that can guarantee high efficiencies for a narrow set of operative conditions; the second point leads to the need to have a reliable propeller model (integrated in a more general power system model) in order to properly analyse and design the whole cooling system.

The efficiency of the propulsion system in general and of the propeller in particular was the key aspect for the flight tests of the ENFICA FC project as they had a direct and important impact on the power required from the fuel cell and the battery and therefore also on the mass of these components.

In order to increase the efficiency of the propeller, the blade diameter should be maximized as shown in eq (1); in fact, when the diameter of the propeller is increased, the delivered power is spread over a larger disk area, and this results in a lower loading of the propeller, which in turn leads to a lower slipstream velocity and thus a higher efficiency. On the contrary, a low value of the slipstream velocity could be critical for the cooling system. Additionally, the diameter is limited by both ground clearance and Mach number constraints. The diameter must, first of all, be kept small enough so that it will not hit the ground during landing to avoid engine and propeller damage. Furthermore, the diameter must be limited to avoid high blade Mach numbers at the tip, as this leads to excessive noise as well as compressibility effects on blade drag, 0.8 is a sensible working maximum Mach number at ISA S/L conditions but a less value may be beneficial in terms of noise reduction.

The ideal efficiency of a propeller can be deduced by using the axial momentum theory, where blade drag effects are neglected (Torenbeek, 1976). Only axial momentum and a uniform increase in velocity over the entire disk area are considered. The ideal efficiency is fixed for a given thrust, flight velocity and propeller radius, and can be written as:

$$\eta_i = \frac{T \cdot V_\infty}{P} = \frac{1}{1 + v_i / V_\infty} \quad \text{with} \quad v_i = \frac{1}{2} \left(\sqrt{V_\infty^2 + \frac{2T}{\rho S}} - V_\infty \right) \quad (1)$$

During the cruising condition, the ideal efficiency is 95% and during the climbing phase it is 88%. It's very important to notice that these two values are the highest that can be obtained and, in practice, considering all the losses, it's impossible to reach these levels.

The optimum propeller efficiency is, instead, the efficiency (excluding energy losses deriving from profile drag or finite wing effects) that has an optimum load distribution as, suggested by Goldstein for a specified number of blades (Munk, 1922)(Reissner, 1940)(D'Angelo, Berardi, & Minisci, 2002) (Wald, 2006). The advantage of using this efficiency is that it presents a maximum value that cannot be exceeded for a given propeller diameter and blade number, but which can be obtained through a proper design. A numerical procedure for the determination of an optimal twist angle and chord distribution, as a function of the distance r from the hub, for an n-blade propeller of radius R, is presented in (D'Angelo, Berardi, & Minisci, 2002) and used here to derive the geometry of the ENFICA-FC propeller. The optimum propeller will minimize the energy loss to provide the required thrust, considering the operating point in terms of forward speed, propeller angular velocity and altitude.

The maximum efficiency of the propeller is obtained if all the airfoils along the blade span are at the maximum efficiency