ENFICA-FC: DESIGN, REALIZATION AND FLIGHT TEST OF ALL ELECTRIC 2-SEAT AIRCRAFT POWERED BY FUEL CELLS

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Abstract

The paper presents the work done by the authors regarding design, realization and flight test of an hydrogen fuel cell general aviation aircraft. The aircraft is developed under the European FP6 program "ENFICA-FC" coordinated by Prof. Giulio Romeo. A general explanation of the design activities is first presented in conjunction with a detailed description of the components of the highly complex power system. Great importance is given to the testing phase of the prototype, showing examples from each testing stage from the single component to the final flight test.

1 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.

The main objective of the ENFICA-FC project is to develop and validate the use of a fuel cell based power system for propulsion of more/all electric aircraft. The fuel cell system is installed in the light sport aircraft RAPID 200 which was flight and performance tested as a proof of functionality and future applicability for inter city aircraft.

The ENFICA-FC consortium, coordinated by Prof. G. Romeo of Politecnico di Torino, consists of 9 partners representing the whole value chain with Aircraft manufacturers (IAI, Evektor and Jihlavan Airplanes), Fuel cells Power system producer (Intelligent Energy), Hydrogen distribution (Air Product), Research Institutes (Politecnico di Torino, Université Libre de Bruxelles and University of Pisa) as well as a SME in the field of administrative management (Metec). Within the course of ENFICA-FC project, which was launched on October 2006, two key objectives was realized:

1) A feasibility study carried out to provide a preliminary definition of new forms of Inter-City aircraft power systems that can be provided by fuel cell technologies (APU, Primary electrical generation supply, Emergency electrical power supply, Landing gear, De-icing system, etc); more over safety, certification & maintenance concepts were defined.

Parametric sizing of different aircraft categories were performed, ranging from two-seat aircraft to 32 passenger small commuters.

Very interesting results have been obtained from the preliminary parametric sizing and analysis of a more-electric 32 passengers regional jet aircraft fuelled by liquid hydrogen. The study has given better understanding of the practical meaning of transition from kerosene to hydrogen in transportation airplanes.

2) A two-seat electric-motor-driven airplane powered by fuel cells was assembled and tested.

The high efficiency existing, two-seat aircraft Rapid 200, manufactured by Jihlavan Aircraft (now Sky Leader), was selected for conversion over more than one hundred light sport aircrafts by the mean of a multi-criteria analysis performed by Politecnico di Torino.

This paper concerns the activities related to the second aforementioned point, focusing on design of the conversion, on practical realization of RAPID200FC and on testing of systems and aircraft.

1 Design of Conversion

After the selection of the proper aircraft for conversion [1] an extensive conversion design activity was carried out; main properties of selected aircraft (powered by Internal Combustion Engine) are reported in table 1.

Table 1

Main Characteristics of the RAPID 200-ICE	
Maximum take off weight	4500 N
Basic empty weight	2980 N
Maximum level speed	260 km/h
Cruise Speed	180-240 km/h
Minimum speed with flaps	48 km/h
Manoeuvring speed	156 km/h
Maximum engine power	80 – 115 hp
Fuel capacity	64-94 l
Endurance	3.5 – 5.5 hrs
Range	760 – 1050 km
Take off distance (15 m)	185-200 m
Wing span	9.9 m
Wing area	11.85 m^2
Aspect ratio	7.8
Overall length	7.0 m

First step was the definition of the demonstrative mission; since the goal of demonstration is to show feasibility of a new concept propulsion system a complete, but limited, mission profile was selected by the consortium. The mission can be summarized as follow:

1. take-off;
2. climbing up to 1000m with a rate of climb of 2.5 m/s;
3. cruising over the airport at approximately 150 km/h for 40 minutes;
4. descending and landing.

Requested mission performances are based on a parametric study and system architecture design (see section 3) done by the authors and reported in [1]; these values were chosen because they could guarantee, with a good confidence as confirmed at the end of conversion activity, that the mission could be flown keeping the total weight around 550 kg, i.e maximum total weight original RAPID200 was tested.

In order to define power requested for mission phases a better understanding of aircraft aerodynamic behavior was needed; for this purpose CFD analysis was performed by the mean of VSAERO commercial code; the analysis concerned not only the overall aircraft, but also critical component to be designed; as an examples CFD results were vital for the design of engine cowl [2] that must guarantee a proper cooling of the different systems installed in the engine bay (see section 3), but also be a passive safety system for prevention of hydrogen accumulation. Moreover CFD results were important to design the complete hydrogen venting system and to predict best locations for static pressure ports.

Polar curve and a CFD result used for computation of required powers are reported in Fig. 1 [Ref. 3].

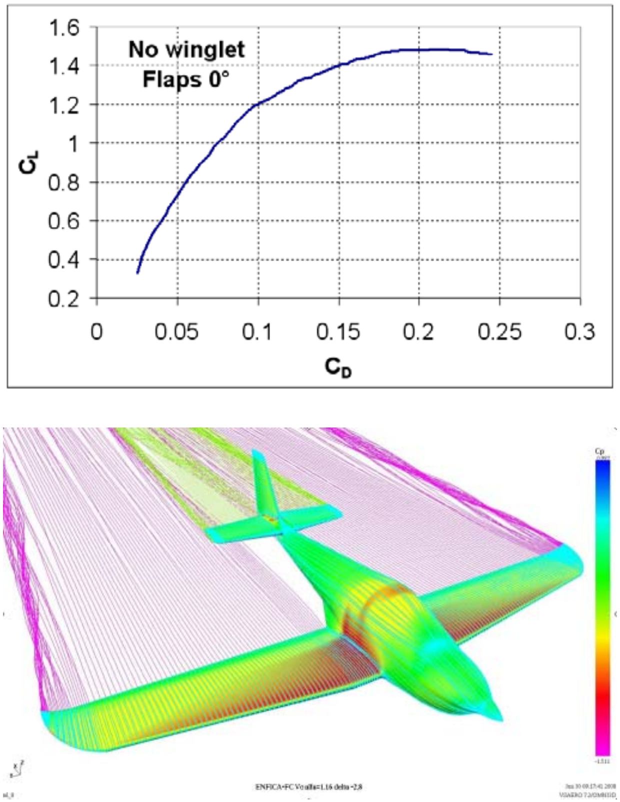

Fig. 1. CFD evaluated polar curves.

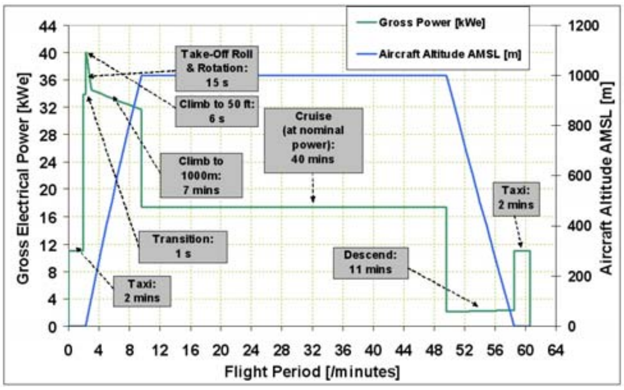

Fig 2. Mission and requested gross power profiles

Required power for each mission phase are finally shown in Fig. 2 and Fig. 3.

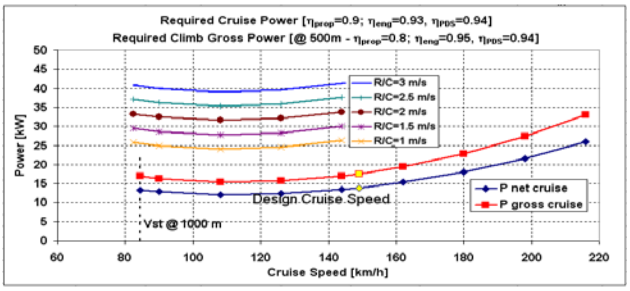

Fig. 3. Required power for cruising at different speeds and for climbing at different speeds and rates of climb.

In order to achieve a flyable aircraft for the prescribed mission a peculiar architecture for the power system was adopted. Relying solely on fuel cells for the entire mission, including take-off, leads to an excessive weight due to the high amount of needed hydrogen (the increase is due mainly to the weight of hydrogen tanks) or a excessive reduction of cruise time at fixed hydrogen tank capacity; for this reason an hybrid battery/fuel cell system was chosen (see section 3.3. and 3.4 for a complete description of the system).

It was decided, however, to limit as much as possible the power supply from the battery during normal operations so that battery is used only during the most power-demanding phases of the mission (take-off and climbing) while fuel cells is always providing all of the necessary power for flight (during cruise and descending) or its maximum power output (approximately 50% of requested power during take-off).

Moreover having two completely separate power source has a strong impact on flight safety, which is the main driver for all decision taken during design; the battery is designed so that it can work as an emergency power source in case of failure of fuel cell, allowing pilot to safely land.

Introduction of the second power source requires a more complex electronic control system; it's necessary indeed that fuel cell is always automatically selected as the main power supplier in order to minimize usage of battery that is "activated" only when requested power exceed fuel cell maximum one; at the same time the controller needs to be able to instantly draw power from battery to replace fuel cell in case of fuel cell malfunction. This controlling function was achieved by integrating the inverter that runs the electric motor with two innovatively designed boosters that modify the voltage of a power source (inverter-side) in order to "activate" or "deactivate" power drawing from them. Innovative design allowed for a very low weight for the entire boosters-inverter hardware (see section 3.5).

Installment of the new power system represent a very important issue form the design point of view. The conventional power system, which the aircraft cell is designed for, is very different from the fuel cell one both for number of items and for volumes of those items, but, above all, balance of the aircraft must be maintained, keeping in mind safety constraints that are particularly important when operating with high pressure hydrogen. An extensive study of the optimum layout has been reported in [1]. Weights of subsystems are reported in Table 2 while the final configuration is shown in Fig. 4.

Some structural component had to be re-designed or introduced in order to make the new layout possible. Engine mount was carefully and heavily re-designed as support for many different subsystems as shown in Fig. 6; a special lightweight support plate for hydrogen tanks was designed; it's capable of meeting the VLA high acceleration requirements (9g) for items that can hit pilot during crash landing.

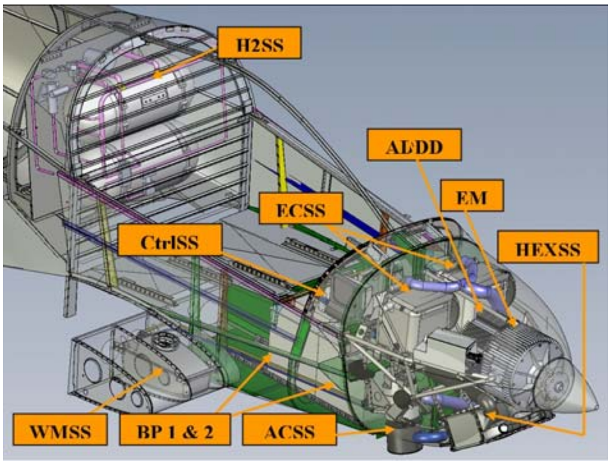

Fig 4. Final lay-out configuration.

Table 2

Component	Mass [kg]
Empty Aircraft [EA]*	221
Electro-Chemical Sun-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 [ADDD]	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.	

Since weight and available power of the converted aircraft strongly differ from the conventional one as well as the behavior of the engine, a new propeller was designed, manufactured and tested for this application.

The aircraft is equipped with data acquisition system (Enclosed Dash Logger MOTEC-EDL2) that measures and records important vehicle parameters (more than fifty) via the general CAN-bus that's used by all onboard devices to communicate with each other. The data is sent by an onboard radio transmitter (Satel Radio) to a radio receiver at the ground control station, allowing the test engineers to monitor, save and post-process data while the aircraft is running its mission. This increases the chance to detect possible system malfunctions.

3 Innovative Power System Description

This section presents an overview of the main features and performances of each subsystem that contributes to flight power generation. In Fig. 5 a schematic of the power system is reported.

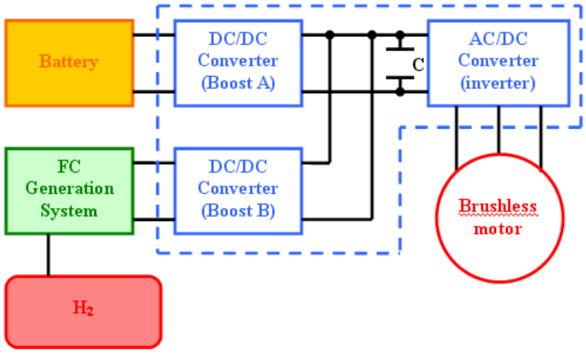

Fig 5. Power system schematic.

3.1 Electric Motor

The motor is a commercial brushless motor produced by Phase Motion Control; main features are reported in table 3.

The brushless motor was chosen by Polito, since the beginning of the project, to guarantee the requested performance just by an air cooling system, eliminating in such way the weight of water cooling.

The motor-case is directly linked to the electronic boards (inverter DC/AC and chopper DC/DC). This can be considered an excellent solution in terms of layout integration and cooling, because the air flow that runs along the wing tabs of the motor goes directly on the external surface of the converter case, carrying on its cooling action (Fig. 6).

3.2 Fuel Cell System

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.

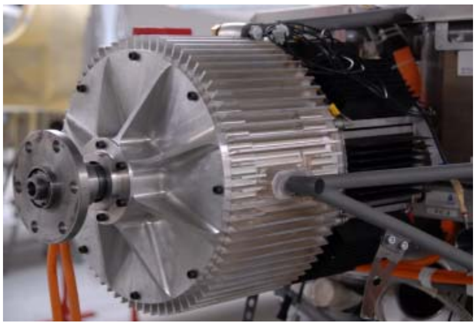

Fig 6. Motor and Converter/Inverter system.

An overview of the overall FC system is shown in Fig. 7.

Table 3

Motor type	PMSM
Nominal Power	46 kW
Nominal torque	187 Nm
Max speed	3000 rpm
Efficiency	> 0.94
Cooling	Forced air
Coolant flow at rated power	> 3 m^3/min
Max environment temperature	40 °C
Maximum Torque	295 Nm
Power at maximum speed &	92 kW
Maximum Service Temp	120 °C

Fig. 7. Fuel cell system assembled in the mock-up fuselage

ECSS - Electro-Chemical Sub System: System consists of two separate fuel cell units. To provide a safe mounting system, the fuel cell stack is enclosed in a lightweight structure that provide also safe ventilation of any hydrogen leak and electrical isolation.

Stacks are designed for a maximum current of 110A.

ACSS - Air Compressors Sub System
The system is designed as two-stage centrifugal compressors in series. It will bring the fresh air from engine cowling inlet and source fuel cell stack with compressed air.

HEXSS – Heat Exchanger Sub System
The heat exchanger assembly is situated in the front part of the engine bay under the electric motor. The fresh air flows through the engine cowling 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. 8.

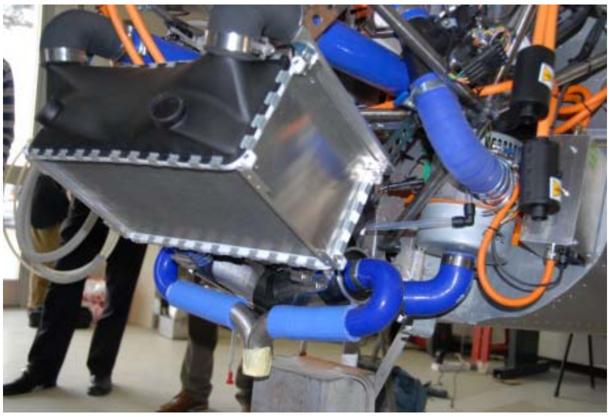

Fig. 8. Installed heat exchanger and cyclone unit.

WMSS – Water Management Sub System
System consists of water tank assembly situated in the right central wing part leading edge and water pump, filter and flow meter situated in the engine bay. The leading edge was originally used as fuel tank. It was necessary to replace the fuel tanks with aerodynamic covers. The ribs were positioned and designed to serve also as the supporting

structure for water tank hinges. In Fig. 9 the first prototype of the water tank is showed. The actual tank can be showed as it's directly integrated in the wing leading edge aluminum sheet.

Fig. 9. Water tank prototype.

CtrlSS - Control Sub System

This system comprises of FCS central communication and control module and Internal Battery Sub System (a battery that is used to start-up the fuel cell).

3.3 Hydrogen Subsystem

The system comprises two Dynatek L026 tanks with accessories (valves, sensors etc.) and it's shown in Fig. 10. Their capacity is 26litres each or 0.6 kg of hydrogen at 350 bar pressure. The whole assembly is installed in the baggage compartment behind the pilot. (see below). It is separated from cockpit by aluminum wall. The tank compartment is sealed from cockpit to avoid any improbable possible H2 leakage into pilot cabin. The tanks are secured with brackets that are mounted to a lightweight construction which is directly attached to the load bearing structure. This solution ensures that all the operational loads and also the crash loads will be properly absorbed by the aircraft structure.
The access to the luggage compartment for refill and inspection of the tanks is trough the side door which can be opened from outside. Refill valve is placed directly behind the door.

3.4 Battery Packs

Two packs of Li-Po batteries (Fig. 11) supply additional energy necessary for take-off and climbing; the pack is able to deliver 20 kW for about 19 minutes. They are stored in two carbon fiber containers (with glass/fiber covers) which are secured with rails to the cabin floor at co-pilot's side. The rails and wheels make manipulation with containers easier.

Fig. 10. Hydrogen storage system.

Fig. 11. Battery packs.

The system produced by Air Energy for Polito presents the features reported in Table 4.

Table 4

Type of cells	Lithium Polymer
Nom. Voltage	207,2V
Nom. Capacity	30Ah
Nom. Energy	6,2 kWh
Energy at 20kW, 20°C	5,8 kWh
EOC Voltage	235V
EOD Voltage	185V
Min power 15min, required	20 kW
Cell Weight	48kg
Weight incl. Case and BMS	51kg with CFRP case
Dimensions	2 modules 220*300*300mm
Charge Time with 3kW charger	3kW/220V-50Hz, 240V 12A

Two possible installation solutions have been adopted:

a) in the front part of pilot cabin (from co-pilot seat up to the engine fire-wall;
b) in the rear part of pilot cabin

The second solution was finally chosen in order to proper obtain the centre of gravity of the airplane.

3.5 Vehicle Control System (AC/DC and DC/DC)

Motor and inverter are powered by both FC and battery. Power converters (boost) raise input voltage and build a direct current bus with variable voltage; voltage is selected by EVCS (Electric Vehicle Control System) in order to optimize motor and inverter operations.

Boosts are necessary for correctly drawing power from both sources; without boosts only the higher-voltage source is effective (usually FC).

Inverter purpose is to properly modulate the direct current bus coming from boosters in order to provide since current to motor phases. Frequency and amplitude are strictly connected with motor rotational speed and torque.

The system, designed and produced by Maver srl for the Enfica-fc project is very compact, very efficient (>97%) and very light (14 kg) (Fig. 12).

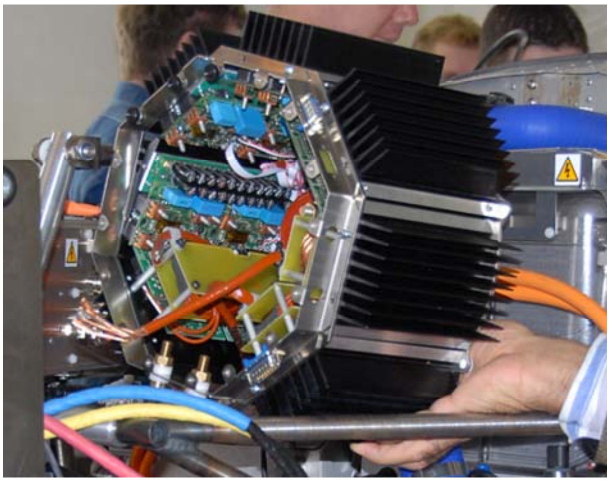

Fig. 12. Integrated vehicle controller.

4 System Testing

Several experimental text activities have been performed at different levels of growing integration. At first manufacturers or suppliers of each sub-system provided results of test on their own system; then a intermediate test campaign was carried on a semi-integrated fuselage mock-up in order to allow for easier modification or replacement of single components; finally the complete system was tested on the real aircraft. This section presents a brief summary of the most significant results obtained during the experimental activities.

4.1 Individual Sub-System Testing

Since the fuel cell system is operating during the entire mission and represents the main power source, it was carefully tested against endurance at its maximum power output. The system was continuously tested by IE for more than 6 hours with no degradation of performances during the experiment. Several 6 hours long tests were performed to prove reliability of the FC system [Ref.4].

Battery system is technologically more mature and so more reliable than fuel cell system; testing hence regarded mainly the safety of the system during charge and discharge. In particular attention was paid to behavior of cell temperatures and the minimum single cell voltage during discharge; this last aspect is very important because, for safety reasons, the battery system isn't provided with automatic cut-off (whose purpose is to protect the battery from any damage that can occur for a too low voltage level) Even if the flight mission was programmed to allow for safe emergency landing in gliding from any point of the flight path, without automatic cut-off, the pilot is able to draw all the energy accumulated in the battery (i.e. the most reliable energy source onboard), eventually damaging cells, in order to land during a fuel cell failure if the gliding range is not enough to reach the airport.

As shown in Fig. 13, a faster voltage drop could be experienced for some of the cell after some charge/discharge cycles or after an excessive discharge below safe limits and a substitution of the less performing cells is needed for this application.

Motor, power electronics and vehicle controller were simultaneously tested. Main concerns about these systems are represented by the temperatures that can be reached during a full duty cycle. As reported in [2] the most stressing conditions are:

- very beginning of take-off phase because of maximum power in conjunction with low speed and so poor cooling for a short time;
- climbing because of maximum power with strong cooling, but for a relatively long time.

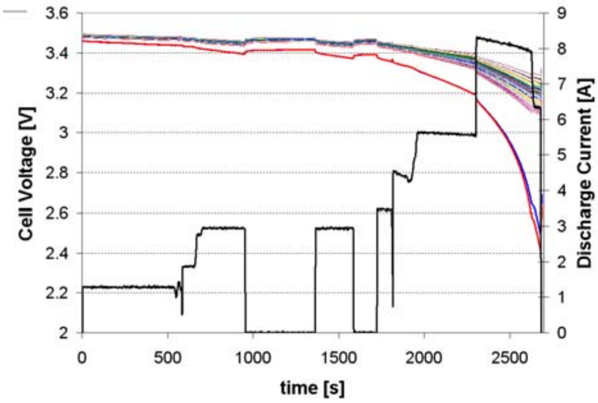

Fig. 13. Battery packs anomalous discharge.

Moreover, starting with those early experiments, the vehicle controller was tested against its capability of being able to immediately switch from the main to the second power source and back without any interruption or unexpected change of motor operation.

Those systems were bench tested with a DC power supplier simulating the two different onboard power sources and an air-blower simulating the air flow due to aircraft speed. A typical power profile adopted during tests is shown in Fig. 14: after a first part representing an extended flight duty cycle, a "power blending" test is carried on, total time is approximately twice the real flight duty cycle.

Temperature behaviors of critical components during the same test are reported in Fig. 15. The maximum temperature reached in the inverter was of 78° C (maximum allowable temp is 120°C), while the maximum temperature reached in the motor was of 80 °C (maximum allowable temp of 180°C).

Hydrogen storage system was tested by tank manufacturer and by the supplier of the entire system against maximum working pressure and burst pressure. Test were conducted according to the test specification identified in ECE draft Regulation Annex 7 B9. Final proven maximum allowable pressure is 438 bar (350 bar is the normal working pressure for this application), while the burst pressure (representing the ultimate load of the tank) is 984 bar.

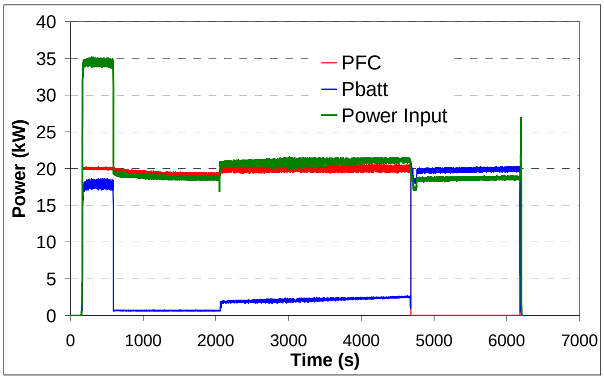

Fig. 14. Power profiles during an extended duty cycle power electronics test

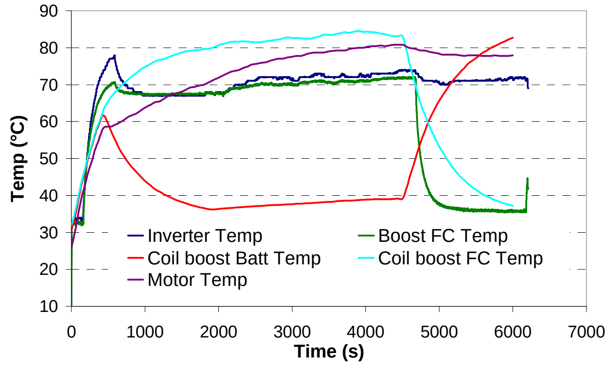

Fig. 15. Temperature profiles during an extended duty cycle power electronics test

4.2 Semi-integrated System Testing

Extensive testing of the semi-integrated system was carried out by POLITO, IE, APL and UNIPI at University of Pisa laboratories. The whole fuel cell system was completely installed in the final configuration on a fuselage mock-up (that can be seen in Fig. 6) as well as telemetry system; the motor/power electronic block was linked to a bench brake; hydrogen was supplied at first from hydrogen bottles installed in a bunker for safety reasons until the system was proven reliable and then last tests were made with the actual hydrogen system with de-rated pressure (200 bar). Each system was provided with air blower simulating the theoretical airflow expected for that particular system. Batteries were replaced by an external generator for most of the tests to prevent deterioration of cells from excessive charge/discharge cycles.

Main goal of this testing stage was to investigate and tune the communication between systems, above all vehicle controller and fuel cell. Moreover fuel cell system is extremely complex and opportune strategies needed to be defined to pilot it during normal and abnormal operations that may occur during flight; extensive testing was hence devoted to software related issues and tuning.

From the hardware point of view attention was paid to same aspects reported in section 4.1, temperatures being the most critical point.

Typical duty cycle test results are shown in Fig. 16 and Fig. 17 for one of the final tests where the system was basically ready for final installation.

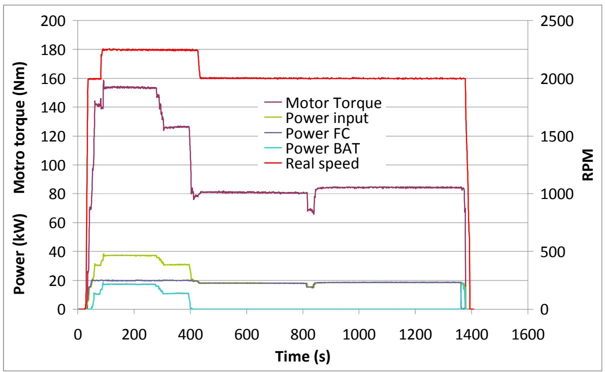

Fig. 16. Power, Torque and RPM profiles during a Typical Duty Cycle.

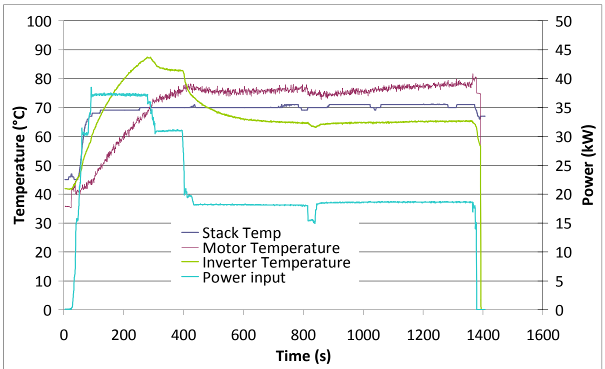

Fig. 17. Temperature profiles during a Typical Duty Cycle.

4.3 Integrated System Testing

The final and most extensive campaign test was the one devoted to the complete aircraft (Fig. 18); ground test and flight test were performed at Reggio Emilia airport with the goal to validate the design and installation of the complete converted aircraft.

This stage mainly investigated the behavior of output power when connected to the real load (i.e. the propeller), behavior of propeller, handling of system partial failures, temperatures with the real cooling system (i.e. cooling system exposed to aircraft speed) and finally aircraft performances in take-off and cruise Again great attention was paid to correct handling of the two onboard power sources; a simulation of fuel cell failure is reported as an example in Fig. 19. Real speed (purple line) has to be considered as a reference performance of the motor and hence the propeller, while power input (green line) is the power requested by the throttle. It can be seen that the system select the fuel cell (red line) as main source until 20 kW are demanded and when this threshold is exceeded the controller starts drawing power from battery (blue line). If for any reason the fuel cell can't provide the requested power, the system immediately demands power from the battery and the performance of the motor doesn't change. Moreover the system tries to recover the fuel cell from its inoperative state and, if successful, re-establish the fuel cell priority.

Several test of this kind were performed simulating different failures and a completely satisfactory behavior was observed.

The effect of the real load was investigated in terms of developed thrust, rpm coupling and absorbed power.

Different propellers were tested other than the one designed for the converted aircraft, in particular a commercial ground variable pitch three-blades propeller was tested as an alternative solution to the two-blade one designed by Politecnico di Torino. Test results for the two-blade propeller are shown in Fig. 20; this was the propeller finally installed and used for flights. Choice of the propeller for this particular aircraft presents more issues than a conventional plane: the torque provided by an electric motor is directly connected to the current supplied to the motor itself which has a physical limit to the current it can handle. This is reflected to the propeller that needs to work with a relatively high rpm to absorb the available power, if this was not the case, the system would be able to develop more power than the amount it can effectively use for generating thrust.

As mentioned above, having the complete system installed allowed for the first time to check the real efficiency of cooling systems (fuel cell, motor, power electronics). In order to investigate this aspect, temperatures were observed during high speed roll-outs which were performed for testing theoretical data about taking-off distances and speeds (Fig. 21)

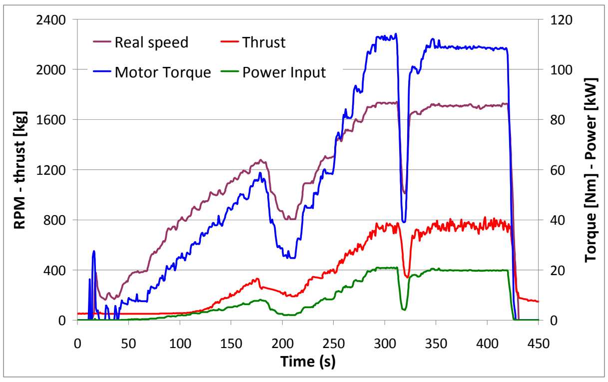

Fig. 20. Two-blade propeller test results

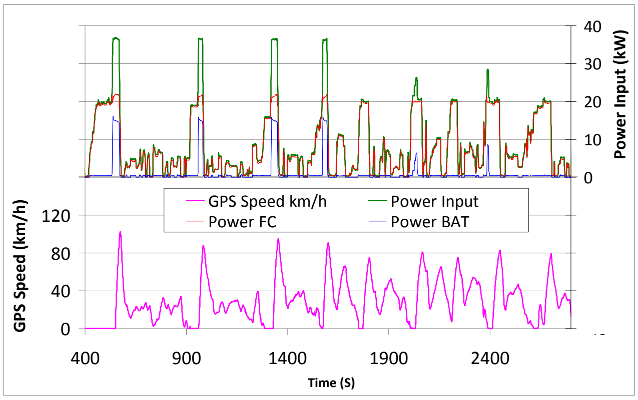

Fig. 21. Summary of high speed roll-outs powers and gps ground speed.

As shown in Fig. 22, cooling systems present a very satisfactory behavior keeping temperatures below admissible limits (external temperature was 19°C). In order to investigate system potential performances for future developing, taking-off without battery support was checked. The aircraft was accelerated up to rotation speed (80 km/h) and, for safety reason, the take-off was aborted before start the climbing phase (Fig. 23). It was possible to reach the rotation speed in 480 m (380 m is the usual distance with fuel cells and battery powers), but further testing should be done for the climbing phase in order to state that the aircraft can effectively run entirely on fuel cell power and careful considerations about reliability have to be made to completely remove batteries from the system.

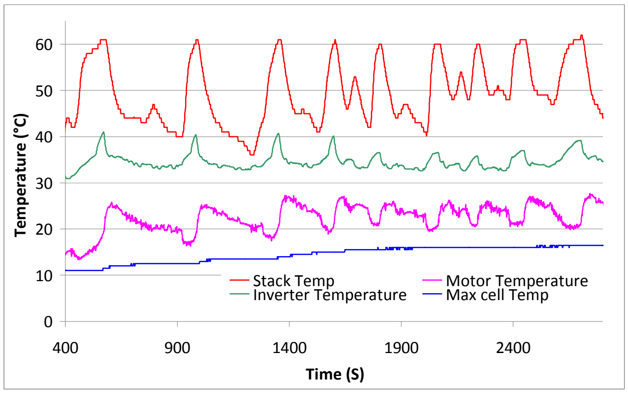

Fig. 22. Summary of high speed roll-outs temperatures

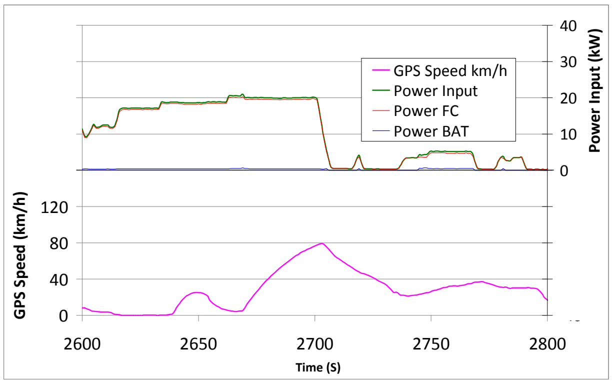

Fig. 23. Fuel cell take-off powers and ground speed.

After this extensive test campaign, the aircraft finally flew at Reggio Emilia airport. Six flights were performed, starting from a first 2 minutes maiden flight and ending with speed world record attempt for electric aircraft powered by fuel cell according to a draft FAI sporting code.

Telemetry recorded flight data are reported in Fig. 24 and 25. Flight path was chosen so that the aircraft was always able to land at the airport or at a close airfield, gliding with no available power. In this particular flight, straight legs are flown with a little altitude loss for world record achievement; in fact the regulation draft requires that the speed is recorded as an average between 3 km straight runs (at least 2, better 4) with a variation of altitude of less 200m. The final obtained endurance is 40 minutes, being the limiting factor not the hydrogen as expected, but water consumption; the tank capacity (8 l) is under sized and this will be optimized as a future development.

As shown the temperatures are kept under their respective limits and the cooling system show better performances than the ones recorded during ground tests.

5 Conclusions

The extensive experimental campaign carried out during ENFICA-FC project, as well as theoretical estimations, proves that fuel cell technologies represent a promising future innovation in aeronautics as a key-enabling technology for all-electric, zero emission, low noise aircrafts.

At the moment, for general aviation aircraft, fuel cells and related technologies seem to need an improvement for gravimetric efficiency point of view; the hydrogen storage system, as an example, weight 52 kg and contains 1.2 kg of hydrogen. Actual gravimetric efficiency doesn’t allow to achieve the same performances as the original aircraft both for flight (speed, endurance) and for payload capability (was impossible to carry the second pilot/passenger for the converted aircraft); a mid-range development would be enough to obtain performances that can be compared to ones belonging to a modern general aviation aircraft.

The real strength of the “all-electric aircraft” concept doesn’t lay in an improvement of the performances, but in the environmentally friendly use of the aircraft itself; such an aircraft could be used in airport surrounded by urban centers, during night and in an environments that could be restricted for polluting vehicles.

6 Acknowledgment

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Fig. 18. RAPID-200.

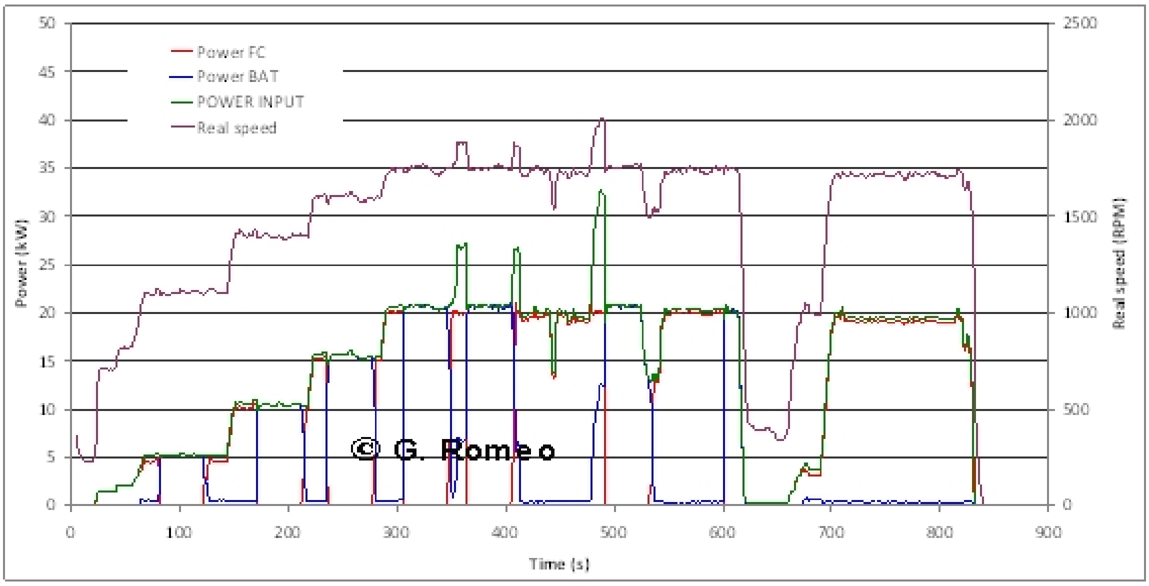

Fig. 19. "Power blending" ground test

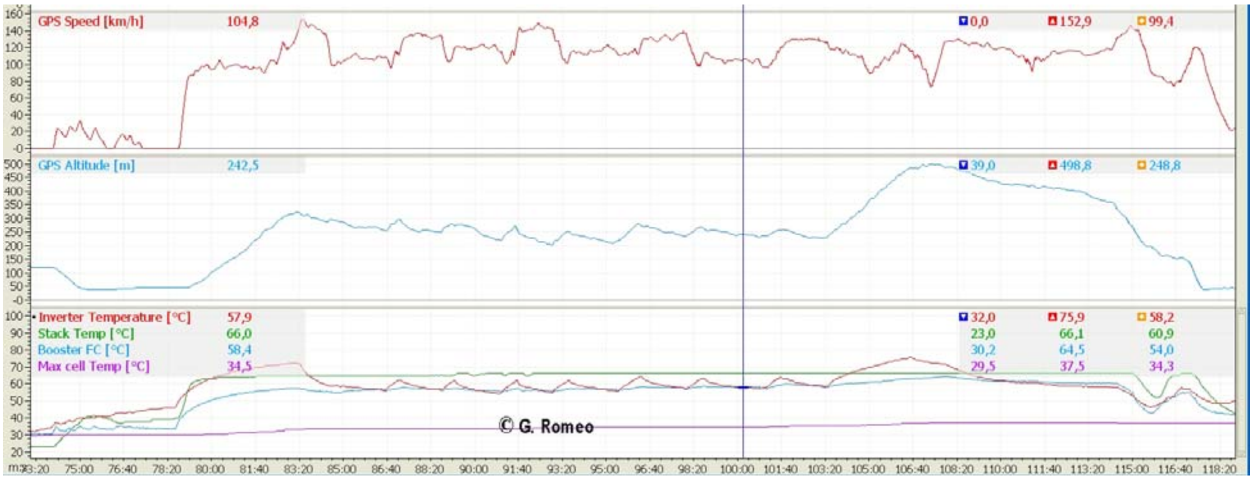

Fig. 24. Flight data.

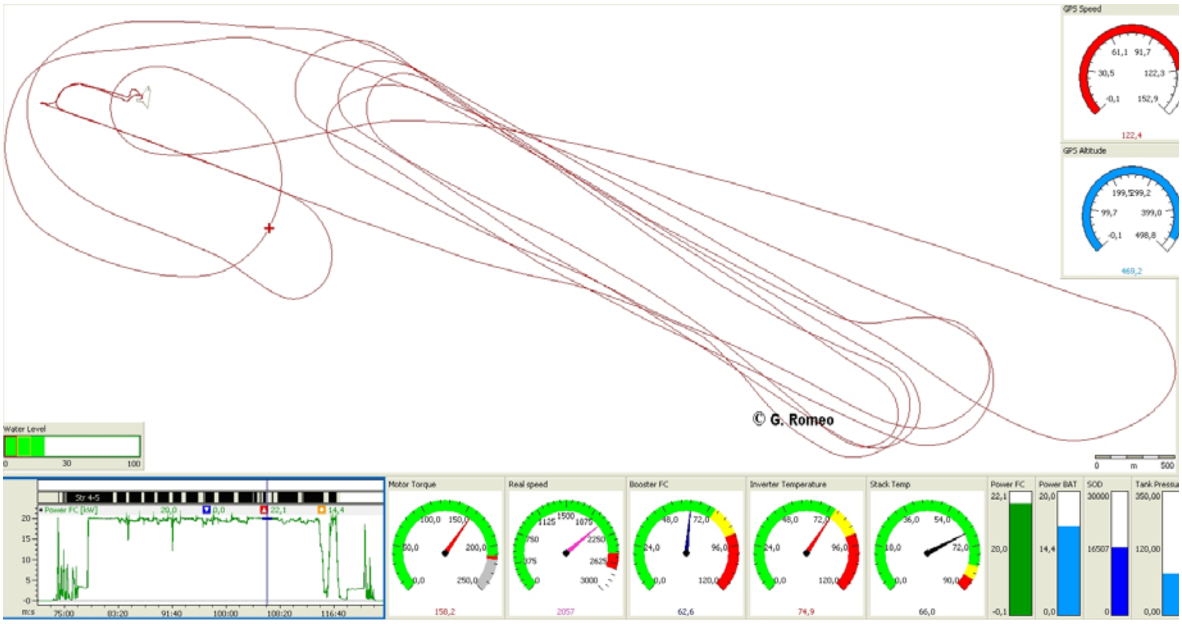

Fig. 25. Flight Path data.