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ENFICA-FC: Design of transport aircraft powered by fuel cell & flight test of zero emission 2-seater aircraft powered by fuel cells fueled by hydrogen

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ABSTRACT

Fuel cells could become the main power source for small general aviation aircraft or could replace APU and internal sub-systems on larger aircraft, to obtain all-electric or more-electric air vehicles. There are several potential advantages of using such a power source, that range from environmental and economic issues to performance and operability aspects. A preliminary design is reported. Also, the paper contains a description of testing activities related to experimental flights of an all-electric general aviation aircraft fueled by hydrogen. Great importance has been given to the testing phase of the prototype and examples of each testing stage are shown ranging from the single components to the final test flights. During the 6 experimental flights a rotation speed of 84 km/h was obtained in 184 m of taxi at power of 35 kW. Level flight was attained at 135 km/h and endurance of 39 min by mean of only a fuel cell power setting (speed world record for the FAI Sporting Code Category C – airplane).

1. General introduction

The hydrogen and fuel cell power based technologies that are rapidly emerging 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.

Hydrogen is expected to provide the fueling source on the medium term and for use in commercial aircraft applications. Fuel cells could become the main power source for small general aviation aircraft or could replace several internal sub-systems on transport aircrafts (emergency power, RAT, cabin power, APU, anti-icing system, landing gear retraction, etc.), to obtain all-electric or more-electric air vehicles.

Early examples derived from Hydrogen based fuel cell automotive system designs are expected to facilitate the early introduction of PEM fuel cell system in aeronautic applications in the near-term. The replacement of combustion engines or *APU* with fuel cells powered electric motors can guarantee a massive reduction of pollution, (since the only emission produced by a fuel cell is water discussion is open if water vapors emitted at high altitude can produce a long period greenhouse effect too) and noise. Nevertheless, the available fuel cell technologies need substantial improvements to meet safe operational requirements in terms of efficiency, reliability, performance, mass/volume, cost and lifetime under flight conditions at altitude and under high and low ambient temperatures in the air and on the ground.

Hydrogen has the advantage of being obtainable from a variety of sources, so that it's less prone to market fluctuation and raises. However, it has to be taken in great consideration the fact that other forms of energy must be used to produce the hydrogen which will be used as fuel. Widespread production, distribution and use of hydrogen will require many innovations and investments to be made in efficient and environmentally-acceptable production systems (i.e. wind energy, solar power, etc), transportation systems, storage systems and usage devices.

Nowadays, the fuel cell system specific energy, defined as the energy output per unit weight, is the greatest issue concerning fuel cell application to aerospace; actually it is about 700 1000 W h/kg but it is estimated that specific energy would increase to 10 kW h/kg at middle term (10 15 years) and to 20 kW h/kg at long term (20 30 years) and this performance will enable an all-electric flight of large commercial aircraft. Moreover, even if hydrogen contains an amount of energy per unit mass three times higher than kerosene, the significantly lower density of hydrogen leads to the necessity to adopt pressurized or cryogenic fuel tanks; either solution means extra weight and volume.

Several general aviation and motor-glider electric vehicles have been produced in these last years to get a more environmentally friendly vehicle. In all these vehicles, the power is supplied by a battery system which introduce a high limitation on flight endurance because of their high weight. Battery specific energy, in fact, is actually limited to 150 200 W h/kg and is expected to increase at middle term to a maximum value of 300 W h/kg, one order lower than fuel cell specific energy expected in long term.

The main objective 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 the use of a fuel cell based power system for the propulsion of more/all electric aircraft. The fuel-cell system was installed in a light sport aircraft RAPID200 which was flight and performance tested as proof of the functionality and future applicability of this system for inter city aircraft. The ENFICA-FC consortium consists of 9 partners representing the whole chain of Aircraft manufacturers (IAI, Evektor and Jihlavan Airplanes), a Fuel cells Power system producer (Intelligent Energy), a Hydrogen distributer (Air Product), Research Institutes (the Politecnico di Torino, the Université Libre de Bruxelles and the University of Pisa) as well as an SME in the field of administrative management (Metec). Within the course of the ENFICA-FC project, which was launched in October 2006, two key objectives were attained:

1) A feasibility study was carried out to provide a preliminary definition of new forms of Inter-City aircraft power systems that could be provided by fuel cell technologies (APU, Primary electrical generation supply, Emergency electrical power supply, Landing gear, De-icing system, etc); the safety, certification and maintenance concepts were also defined. Parametric sizing of different aircraft categories was performed; these ranged from two-seater aircraft to small 32 passenger commuters. Very interesting results were obtained from the preliminary parametric sizing and analysis of a more-electric 32 passenger regional jet aircraft fueled by liquid hydrogen. The study has led to a better understanding of the practical meaning of transition from kerosene to hydrogen in transportation airplanes.
2) A two-seater electric-motor-driven airplane, powered by fuel cells, was assembled and tested. The high efficiency, two-seater aircraft Rapid200, manufactured by Jihlavan Aircraft (now Sky Leader), was selected for conversion from over more than one hundred light sport aircraft through a multi-criteria analysis performed by the Politecnico di Torino. After the selection of the aircraft for conversion [1] an extensive conversion design activity was undertaken. The first step was to define the demonstrative mission; a complete, but limited, mission profile was selected by the consortium since the demonstration goal was to show the feasibility of a new concept propulsion system. The requested mission performances were based on a parametric study and system architecture design which was conducted by the authors and is reported in [1]; mission properties were chosen because they could guarantee that the mission could be flown while keeping the total weight at around 550 kg, i.e. the maximum total weight at which original RAPID200 was tested. This result was confirmed at the end of the conversion activity. Because the fuel cell system was heavier than combustion engine system it was necessary to design the converted Rapid200-FC just with a single pilot on board in order to strictly satisfy the 550 kg limit of Total Weight.

A better understanding of the aerodynamic behavior of the aircraft was needed to define the power requested for the mission phases; a CFD analysis was performed, for this purpose, by the mean of the VSAERO commercial code; the analysis concerned not only the overall aircraft, but also the critical components that had to be designed; as an example, the CFD results were vital for the design of the engine cowl [2] which 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 the prevention of hydrogen accumulation. Moreover the CFD results were important to design the complete hydrogen venting system and to predict the best locations for the static pressure ports.

2. More-electric and all-electric transport aircraft feasibility studies

The first step to undertake for a More-Electric transport aircraft analysis is to define which non-electric systems can be replaced by an electrical counterpart. This step is crucial because it defines the duty cycle of the fuel cell system and hence its design.

During ENFICA-FC project a wide variety of different aircraft categories and concepts were evaluated and an extensive database of preliminary solutions were produced; since this electrical system conversion has to be made on a single case basis that depends on categories and reference models, a complete description of conclusions can’t be made here.

As an example, the case of regional jet based on a real aircraft designed by one of the ENFICA-FC consortium is reported. In this case the system that can be replaced and redesigned are:

- ◇ Wing flaps: they are currently controlled hydraulically. The hydraulic actuator of the flaps control can be simply replaced by an electrical actuator.
- ◇ The landing gear is retracted by mean of hydraulic struts with possibility of emergency extending. Every landing gear leg is controlled by one hydraulic strut equipped with the mechanical lock in both extreme positions. The main landing gear actuator is double acting hydraulic cylinder with single piston rod. The extreme positions of the actuator are secured by mechanical segment locks. The locked positions are signalized by electro-block. Further the actuator is equipped with a hydraulic block for gear emergency

extending. The hydraulic actuators of nose and main landing gear retracting will be replaced by an electrical actuator. The electrical actuator must allow emergency retracting of the landing gear.

- ◇ Brakes: the original design provides the use of three-disk six-piston hydraulically controlled brakes. The brake system is optionally equipped with the anti-block system (ABS). The pilot controls hydraulic cylinders by means of levers on the pedals of foot control. Electronic control unit, based on comparison of the relevant main landing gear wheel with the nose landing gear wheel, controls the electro hydraulic element which controls pressure in an appropriate branch of the main landing gear brake system. The hydraulic brake system can be replaced by electro-magnetic brake system.
- ◇ Steering system: the nose landing gear is controlled by means of the hydro-mechanical cylinder during movement of the aircraft on the ground. The secondary function of the hydraulic cylinder of the nose wheel steering is shimmy damping.
- ◇ The air conditioning system consists of the heating system and the ventilation and cooling system. The heating system uses bleed air for heating. The ventilation system is made by mean of heating system. The fresh air is led from NACA inlet through the heating system to the cabin. Optionally the airplane can be equipped by the cooling system. Hot air is used for heating. Hot air is led from engines via shut-off valves through pipes in the area of the wing leading edge.

Cold external air is led to the mixing chamber by means of NACA-inlets. There are several possibilities of heating system solution:

1) The heating system is not changed. Bleed air is the source of hot air.
2) Hot air is taken from fuel cells: it is assumed PEMFC (Proton Exchange Membrane Fuel Cell) system will be used. As a fuel hydrogen is used. The current heating system has to be redesigned. Air is heated with the heat produced by fuel cells. A heat exchanger should be used because exhaust gas is poor in oxygen and rich in nitrogen and should not be used directly for cabin heating.
3) Hot air is taken partially from engines and partially from fuel cells: This system is a combination of the previously mentioned systems (1) and (2). In this system less air can be taken from engines. A part of necessary hot air is to be covered by fuel cells and a part is to be covered by heat from electric heating.

The ventilation system is made by means of the heating system. In the cold environment the fresh air inlet is provided with hot air supply through the heating system. In the warm environment ventilation in the cabin in ensured by the heating system with closed supply of hot air from the compressor. The aircraft can be equipped with the air conditioning cooling unit as an option. This unit is composed of the compressor-condensation unit and two evaporators. The evaporators are equipped with the ventilators which take air from the cabin via inlets in the ceiling section, cooling it down and returning back to the cabin space. Distribution of medium is made by means of the insulated tubing.

- ◇ Pneumatic boot de-icing system: Currently profiled surfaces are equipped with the pneumatic de-icing system based on the principle of mechanical deformation of a flexible rubber coat surface which is glued on the leading edges of the profiled surfaces. The cooled bleed air is used in the de-icing system for inflating of the rubber coat. A system which can be used for de-icing is the electro-impulse de-icing system. Ice is shattered, de-bonded, and expelled from a surface by a hammer-like blow delivered electro-dynamically. Removal of the ice shard is aided by turbulent airflow; thus, relatively low electrical energy is required. Physically, the system consists of ribbon-wire coils rigidly supported inside the aircraft surface to be de-iced, but separated from the skin surface by a small air gap. A sudden high voltage electric current is discharged through the coil. They must have low resistance and inductance to permit the discharge to be very rapid, typically less than one-half millisecond in duration. A strong electric field forms and collapses, inducting eddy currents in the aircraft skin. The eddy current and coil current fields are mutually repulsive, resulting in a toroidal-shaped pressure on the skin opposite the coil. Actual surface deflection is small, but acceleration is rapid.

At the same time, more theoretical type studies have been carried out on the feasibility of an All-Electric transport aircraft (in collaboration by the Israel Aerospace Industry, Université Libre de Bruxelles and Evektor partners). These will not have an immediate practical application in the initial stages because of the present technological limits, but have the aim of using zero emission propellers in the future to equip aircraft for 10 15 passengers in the intercity sector. Although with slightly smaller performances a preliminary configuration was designed and reported in Fig. 1. An increase of 11.5% in takeoff weight for the projected intermediate technology and only 2.1% for the projected advanced technology. The all-electric fuel cells Inter-City airplane is not in the same performance category (Range and maximum cruise speed) as the small commuter turbo-prop airplane. The range is decreased from 2300 km to 1500 km and the maximum cruise velocity is decreased from 550 km/h to 320 km/h. Since Fuel cells are not used, so far, in aeronautical applications, the existing certification regulations do not properly address the specific features of this novel technology. Some changes to the existing regulation are required in order to encompass the special features of fuel cells. In addition, some new special conditions need to be formulized.

Involvement of certification experts in the early stages of the development is crucial for embedding the required safety features in the evolving FC systems that will provide a level of safety that is equivalent to that provided by the existing technology.

The real strength of the "all-electric aircraft" concept doesn't lay only in an improvement of the performances, but in the environmentally friendly use of the aircraft itself (among the other also the noise pollution and low emissions particularly important for commuter airplanes that usually takeoff and land from urban areas). The possibility to take-off and land within the noise abatement regulations set for small airfields, in urban areas and near population centers, will allow the use of these airfields during the late night hours when the noise abatement regulations are even more stringent. Other advantages of this commuter all electric aircrafts are: high reliability, low maintenance and only slight reduction in engine performance due to altitude.

3. Power system description of the 2-seater airplane powered by fuel cells

A particular architecture was adopted for the power system in order to obtain an aircraft that could fly the prescribed mission [3]. Relying solely on fuel cells for the entire mission, including take-off, leads to an excessive weight due to the required large fuel cell system at high power (40 kW); for this reason a hybrid battery/fuel cell system was chosen (see the following sections for a complete description of the sub-systems).

It was decided to limit the power supply from the battery during normal cruising operations as much as possible so that the battery would only be used during the most power-demanding phases of the mission (take-off and climbing); the fuel cells always work up to 20 kW, which is their maximum power output (approximately 50% of the power requested during take-off) for all the flight phases (take-off, climbing, cruising and descending). Moreover, having two completely separate power sources has an important impact on flight safety, which was the main driver of all the decision taken during the design phase; the battery was designed to supply 20 kW for 18 min so that it could work as an emergency power source in the case of the improbable failure of fuel cell, in order to allow the pilot to land safely.

The introduction of the second power source required a more complex electronic control system; the fuel cell was automatically selected as the main power supplier to minimize the usage of the battery, which is "activated" only when power that exceeds the fuel cell maximum is requested; at the same time, the controller needs to be able to instantly draw power from the battery to replace the fuel cell power in the case of a fuel cell malfunction. This controlling function was achieved by integrating the inverter that runs the electric motor with two innovatively boosters (designed and manufactured by Mavel srl, Italy) which modify the voltage of a power source (inverter-side) in order to "activate" or "deactivate" them as needed. The innovative design ensured a very low weight for the entire booster-inverter hardware set. The weights of subsystems are reported in Table 1 and a schematic of the power system is reported in Fig. 2.

The engine is a brushless electric motor produced by Phase Motion Control, it relies on air cooling and this has led to a saving in the weight as a water cooling system is no longer required. The motor-case was linked directly to the electronic boards (DC/AC inverter and DC/DC chopper). This can be considered an excellent solution, in terms of layout integration and cooling, because the air flow that runs along the motor wing tabs goes directly to the external surface of the converter case, where it continues to carry out its cooling action. The fuel cell system, which is able to provide 20 kW of net unregulated power, consists of:

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

An overview of the whole fuel cell system in its final configuration and completely installed on a fuselage mock-up is shown in Fig. 3.

The Electro-Chemical Sub System (ECSS) consists of two separate fuel cell units. In order to provide a safe mounting system, the fuel cell stack was enclosed in a lightweight structure that also provides safe ventilation of any hydrogen leak and electrical isolation. The stacks were designed for a maximum current of 110 A. The Air Compressors Sub System (ACSS) was designed as two-stage centrifugal compressors in series. This system brings fresh air from the engine cowling inlet and feeds fuel cell stack with compressed air. The heat exchanger assembly (HEXSS) was placed 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 the fuel cell stacks and leaves the engine bay through the outlet opening at the front gear housing. The cooled waste water air mixture arrives at the cyclone where water is separated from air and directed back to the water tank to be re-used. The Water Management Sub System (WMSS) consists of a water tank assembly situated in the right central wing leading edge part (originally occupied by fuel tanks) and a water pump, filter and flow meter situated in the engine bay. Finally, the Control Sub System (CtrlSS) comprises an FCS central communication and control module and an Internal Battery Sub System (a battery that is used to start-up the fuel cell). All the system described above (ECSS, ACSS, HEXSS, WMSS and CtrlSS) are shown the Fig. 4

The hydrogen storage and distribution system was one of the most important systems, from the conversion point of view; its volumes, weights and important impact on safety made it the starting point of each configuration designed during the project. The system consists of two Dynatek L026 tanks with accessories and it is shown in its final configuration in Fig. 5. These tanks have a capacity of 26 L each and they were manufactured for a working pressure of 350 bar (leading to a total H_2 mass capacity of 1.2 kg). The whole assembly was installed in the baggage compartment behind the pilot, and it was separated from the cockpit by an aluminum wall. The tank compartment was sealed off from the cockpit to avoid any H_2 leakage into the cabin. The tanks were secured with brackets mounted onto a lightweight construction which was directly attached to the load bearing structure. This solution ensures that all the operational loads and also the crash loads are properly absorbed by the aircraft structure.

Access to the luggage compartment, for the refilling and inspection of the tanks, is through the side door, which can be opened from outside. A refill valve was placed directly behind the door. Pressure regulators were installed in the former baggage compartment in order to ensure that the hydrogen flowing from the tanks to the fuel cell crosses the cabin at almost atmospheric pressure. The tank compartment was equipped with a passive venting system, which is aerodynamically activated during normal operations and with emergency activated relief valves (over-pressure and over-temperature).

Two Li Po battery packs supply the additional energy that is necessary for take-off and climbing; packs (manufactured by Air Energy) are able to deliver 20 kW for 18 min. They are stored in two carbon fiber containers (and glass/fibre covers) which are secured with rails to the cabin floor on the co-pilot's side. The rails were necessary to remove the batteries easily for safe recharging operations; moreover, the batteries can be placed in different positions in the cabin and this allows a center of gravity shift, when necessary.

As stated before the presence of two different power sources and the will to fly relying only on fuel cells as much as possible, without compromising safety, led to the necessity of properly managing interaction between the fuel cell and the battery pack. As shown in Fig. 2, the power system includes a power electronics management unit that consists of two DC/DC converters (boosters) and an AC/DC inverter, whose function is to control the brushless motor. The boosters raise the input voltage so that only the selected power source becomes effective; without boosters, the higher voltage source would be the only one power is drawn from, and this doesn't allow correct selection. The purpose of the inverter is to properly modulate the direct current bus coming from the boosters in order to provide a sine current to the motor phases. The frequency and amplitude are closely connected to the rotational speed and torque of the motor, and hence to the aircraft performances. The whole system described above and shown in Fig. 6 was designed, produced and integrated into a single module, by Mavel srl for the Enfica-fc project. The system is very compact, very efficient (>97%) and very light (14 kg).

4. Testing the system

Several experimental testing activities were performed at different levels of integration. Initially, the manufacturers or suppliers of each sub-system provided test results on their own systems; then an intermediate test campaign was carried on a semi-integrated fuselage mock-up in order to allow easier modifications or replacements of the single components to be made; 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 operates during the entire mission and represents the main power source, it was carefully tested for endurance at its maximum power output. The system was continuously tested by IE for more than 6 h and no degradation of the performances were registered during the experiment. Several 6 h long tests were performed to prove the reliability of the FC system [4]. The battery system is technologically more developed and so more reliable than the fuel cell system; the testing hence mainly regarded the safety of the system during charging and discharging. Attention was paid in particular to the behavior of the cell temperatures and the minimum single cell voltage during discharge; this latter aspect is very important because, for safety reasons, the battery system is not provided with an automatic cut-off (which has the purpose of protecting the battery from any damage that could occur because of a too low voltage level). Even though the flight mission was programmed to allow for safe gliding emergency landing from any point of the flight path, without automatic cut-off, the pilot is able to draw on all the energy accumulated in the battery (i.e. the most reliable energy source onboard), possibly damaging the cells, in order to land during a fuel cell failure if the gliding range is not sufficient enough to reach the airport. Some of the cells could experience a faster voltage drop after some charge/discharge cycles or after an excessive discharge below safe limits (Fig. 7) and a substitution of the cells that would performing less was needed for this application.

The motor, power electronics and vehicle controller were tested simultaneously. The main concerns about these systems pertain to the temperatures that can be reached during a full duty cycle. The most stressing conditions are [2]:

- At the very beginning of the take-off phase, because of the maximum power in conjunction with the low speed and there is therefore limited cooling for a short period;
- When climbing, because of the maximum power necessary for a relatively long time, although there is substantial cooling.

Moreover, starting with the early experiments, the vehicle controller was tested for its capability to be able to switch immediately from the main to the second power source and back without any interruption or unexpected change in motor operations. These 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 the tests is shown in Fig. 8: after a first part, representing an extended flight duty cycle, a "power blending" test was carried out; the total time was approximately twice the real flight duty cycle. The behavior of the temperature of the critical components during the same test is reported in Fig. 9. The maximum temperature reached in the inverter was 78 °C (the maximum allowable temperature is 120 °C), while the maximum temperature reached in the motor was 80 °C (the maximum allowable temperature is 180 °C). The hydrogen storage system was tested by the tank manufacturer and by the supplier of the entire system for the maximum working pressure and burst pressure. The tests were conducted according to the test specification identified in ECE draft Regulation Annex 7 B9. The final maximum allowable pressure is 438 bar (350 bar is the normal working pressure of this application), while the burst pressure (representing the ultimate load of the tank) is 984 bar.

4.2. *Testing of the semi-integrated system*

Extensive testing of the semi-integrated system was carried out by POLITO, IE, APL and UNIPI at the University of Pisa laboratories. The whole fuel cell system in its final configuration, was completely installed on a fuselage mock-up (Fig. 3) together with the telemetry system; the motor/power electronic block was linked to a bench brake; hydrogen was first supplied from hydrogen bottles located in a bunker, for safety reasons, until the system proved to be reliable; other tests were then carried out with the actual hydrogen system with de-rated pressure (200 bar). Each system was provided with an air blower that simulated the theoretical airflow expected for that particular system. The batteries were replaced by an external generator for most of the tests to prevent deterioration of the cells due to excessive charge/discharge cycles. The main goal of this testing stage was to investigate and tune the communication between the systems, above all the vehicle controller and fuel cell. Moreover, as the fuel cell system is extremely complex and opportune strategies needed to be defined to pilot it during the normal and abnormal operations that may occur during flight operations, extensive testing was devoted to software related issues and tuning. From the hardware point of view, attention was paid to the same aspects reported in previous section, the temperatures being the most critical issue. Some typical duty cycle test results are shown in Figs. 10 and 11 for one of the final tests, where the system was basically ready for final installation.

4.3. *Testing of the integrated system*

The final and most extensive test campaign was devoted to the complete aircraft; the ground tests and flight tests were performed at the Reggio Emilia airport with the goal of validating the design and installation of the complete converted aircraft. This stage mainly involved the investigation of the behavior of the output power when connected to the real load (i.e. the propeller), the behavior of the propeller, the handling of partial failures of the system, the temperatures with the real cooling system (i.e. the cooling system exposed to aircraft speed) and finally of the aircraft performances during take-off and cruising. Again great attention was paid to correct the handling of the two onboard power sources; a simulation of fuel cell failure is reported as an example in Fig. 12.

The real speed (purple line) has to be considered as a reference performance of the motor and hence of the propeller, while the power input (green line) is the power requested by the throttle. It can be seen that the system selects the fuel cell (red line) as the main source until 20 kW are required and when this threshold is exceeded, the controller starts drawing power from the battery (blue line). If, for any reason, the fuel cell cannot provide the requested power, the system immediately demands power from the battery, but the performance of the motor does not change. Moreover, the system tries to recover the fuel cell from its inoperative state and, if successful, to re-establish the fuel cell priority.

Several tests of this kind were performed, simulating different failures, and completely satisfactory behavior was observed. The effect of the real load was investigated in terms of developed thrust, rpm coupling and absorbed power. As mentioned above, having the complete system installed allowed to be checked for the first time the real efficiency of the cooling systems (fuel cell, motor and power electronics). In order to investigate this aspect, the temperatures were observed during high speed roll-outs, which were performed to test the theoretical data pertaining to the take-off distances and speeds (Fig. 13).

As shown in Fig. 14, the cooling systems showed very satisfactory behavior, and the temperatures were kept below the admissible limits (the external temperature was 19 °C).

In order to investigate the potential performances of the system for future developments, it was decided to check take-off without battery support. The aircraft was accelerated up to rotation speed (80 km/h) and, for safety reasons, the take-off was aborted before the climbing phase started (Fig. 15). It was possible to reach the rotation speed in 350 m (180 m is the usual distance when 35 kW of power is supplied by both fuel cells and battery), but further testing should be carried out for the climbing phase in order to be sure that the aircraft can effectively run entirely on fuel cell power, and careful considerations have to be made on reliability before completely removing the batteries from the system.

4.4. *Flight tests*

After the extensive test campaign, the aircraft was finally flown at Reggio Emilia airport (Fig. 16). Six flights were performed, first with a 2 min maiden flight and ending up with the world speed record for electric aircraft powered by fuel cells, according to a draft FAI sporting code, being broken. The 350 bar APL S100 hydrogen refueling system was installed at the Reggio Emilia airfield for these tests.

Six flights were performed and the telemetry-recorded flight data for mission 3 are reported in Fig. 17 as an example of a significant flight in terms of endurance. GPS speed and altitude and main electrical parameters are reported as function of flight time. The flight area was chosen so that the aircraft was always able to land at the airport or at another airfield close by, while gliding with no available power. The final endurance obtained during this particular flight was 40 min (Fig. 17), the limiting factor not being the hydrogen, as expected, but the water consumption; the capacity of the water tank (8 L) is under sized and this will be optimized in a future development. As shown, the temperatures were kept under their respective limits and the cooling system showed better performances than the ones recorded during the ground tests.

An FAI certified GPS data logger (LX Navigation Colibri) was also installed on board to record the ground speed, flight altitude and flight path during the tests. According to the FAI draft rule for electrically powered flights, the speed was measured during two continuous 3 km long runs and with an altitude variation of less than 100 m between the start and the finish points. The flight path and altitude variations of the flight n.3 are shown in Fig. 18.

The main results obtained during flights were:

- A maximum endurance of 39 min was recorded.
- A maximum speed of 135 km/h was recorded during runs 6 7.
- A greater maximum speed than 158 km/h was reached during a free flight.

- A minimum pressure of 70 bar was measured in the hydrogen tank at the end of the flights. 5.9 bar/min were approximately consumed during the flight; thus about 10 min more could be possible and this would increase the flight endurance to 49 min.
- A minimum value of the water level of about 15% was reached.
- The total GPS Horizontal Path Length (Taxi + roll out + climb + horizontal flight + landing) was 76.5 km

5. Conclusions

The extensive experimental campaign carried out during the ENFICA-FC project, as well as the theoretical estimations, have proved that fuel cell technologies represent a promising future innovation in aeronautics as a key-enabling technology for all-electric, zero emission, low noise aircraft. A new world speed record of 135 km/h and endurance of 39 min was established during several flights for Category C (airplane) of the FAI Sporting Code. The previous record was established by the Boeing Research & Technology Centre (Madrid) in their first hydrogen flight (120 km/h for 20 min, but for a motor-glider, Class D, FAI Sporting Code); DLR also flew in 2009 but with a motor-glider (Class D, FAI Sporting Code) powered by fuel cells.

Higher flight speed values were measured during the free flight with altitude variations of 200 m. Higher speeds than 155 km/h were measured several times, with a top speed of 180 km/h, which was measured during several diving and pull-up maneuver tests.

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. 2.8 h of block time and 2 h of effective flight were obtained during these 6 tests for a total path of 237 km.

The results obtained during the flights can be considered as a further step in the European and World Aeronautics Science field toward introducing completely clean energy (ZERO EMISSION).

At the moment, for general aviation aircraft, fuel cells and the related technologies seem to need improvement from the gravimetric efficiency point of view; for example the hydrogen storage system, weights 52 kg and contains 1.2 kg of hydrogen.

The actual gravimetric efficiency does not allow the same performances to be achieved as the original aircraft, both as far as flights (speed, endurance) and for the payload capability are concerned (it was impossible to carry a second pilot/passenger in the converted aircraft); a mid-range development would be sufficient to obtain performances that could be compared to those of to a modern general aviation aircraft.

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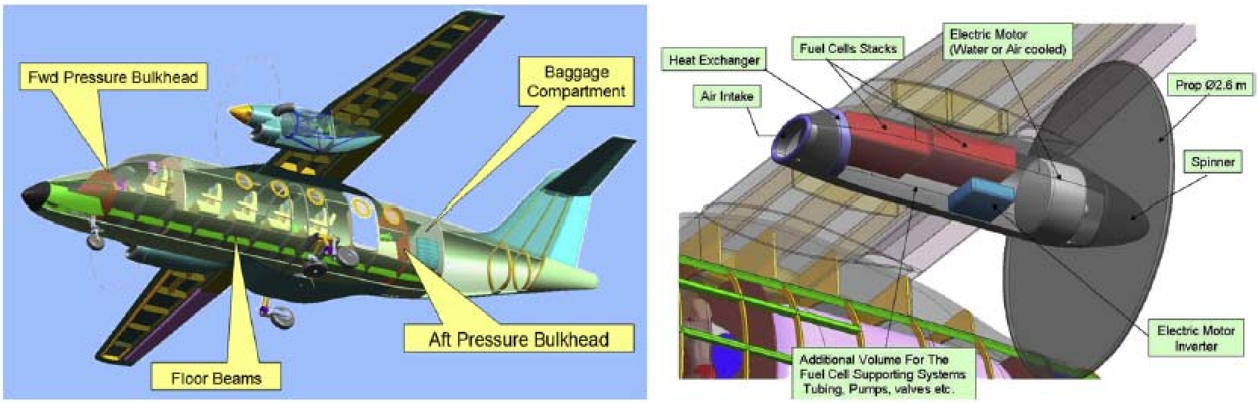

Fig. 1 All-electric intercity airplane powered by fuel cell fueled by hydrogen.

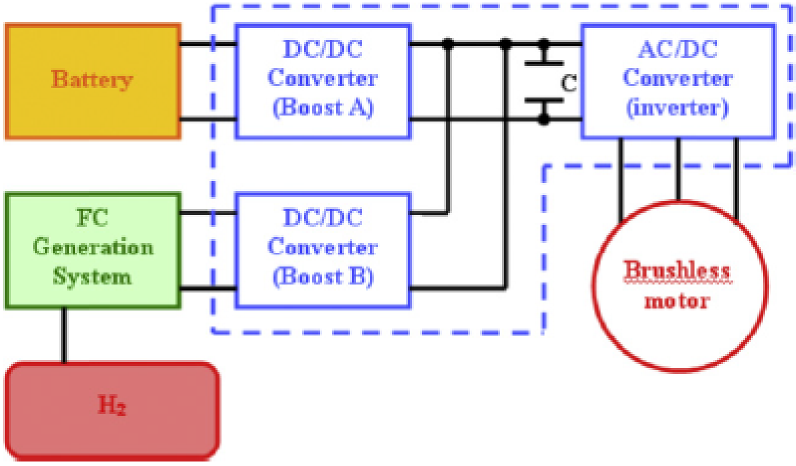

Fig. 2 Rapid200-FC power system schematic.

Fig. 3 Fuel cell system assembled in the mock-up fuselage.

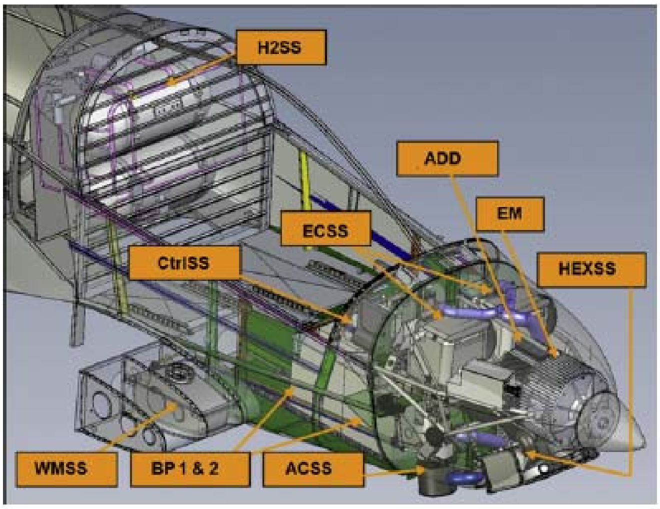

Fig. 4 Schematic view of new fuel cell and electrical system.

Fig. 5 Hydrogen storage system.

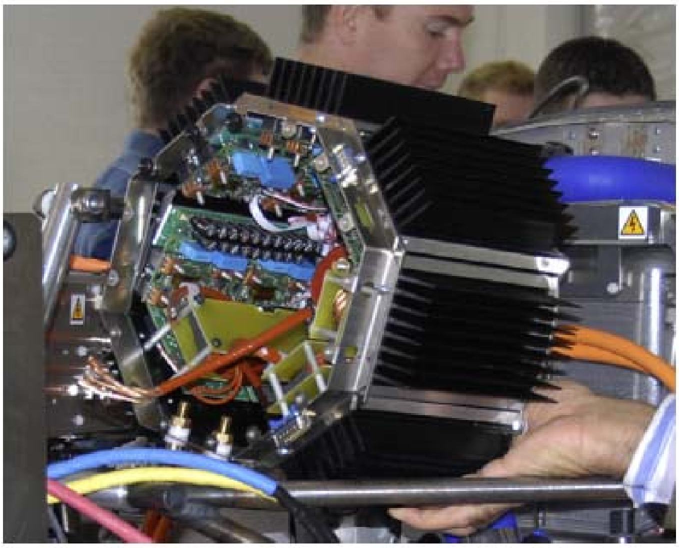

Fig. 6 Integrated converter, inverter and vehicle controller system.

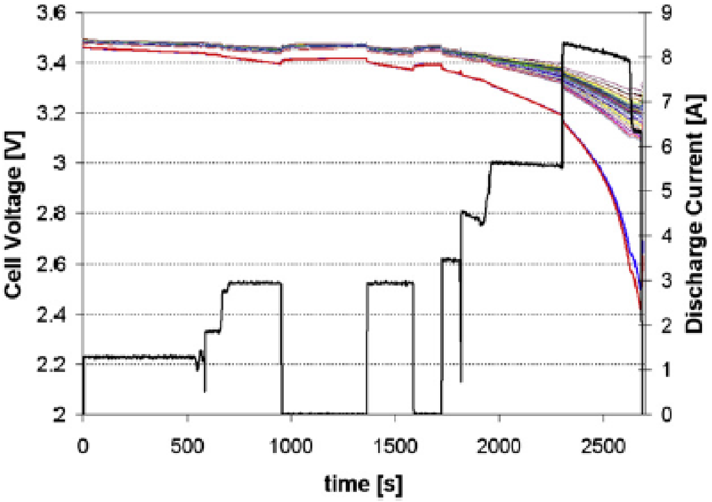

Fig. 7 Battery packs anomalous discharge.

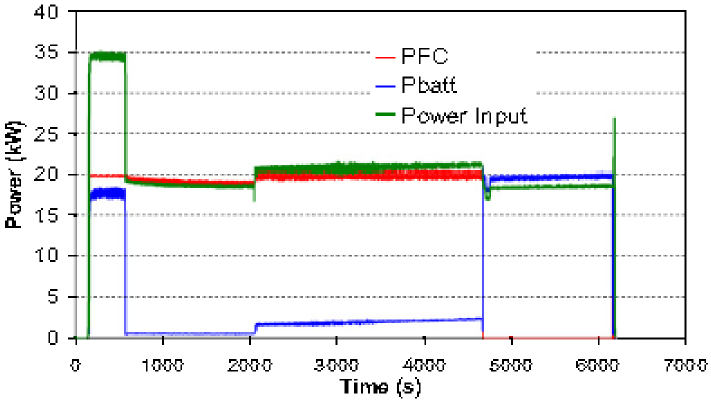

Fig. 8 Power profiles during an extended duty cycle power electronics test.

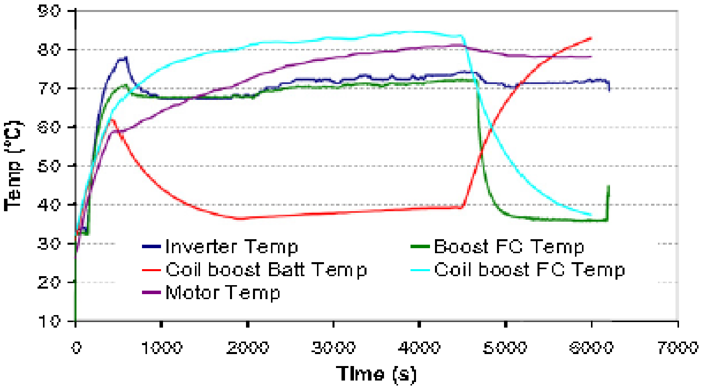

Fig. 9 Temperature profiles during an extended duty cycle power electronics test.

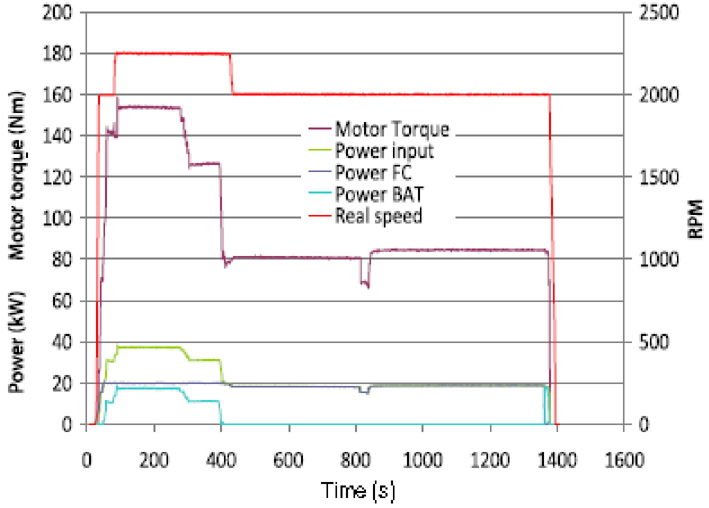

Fig. 10 Power, torque and RPM profiles during a typical duty cycle.

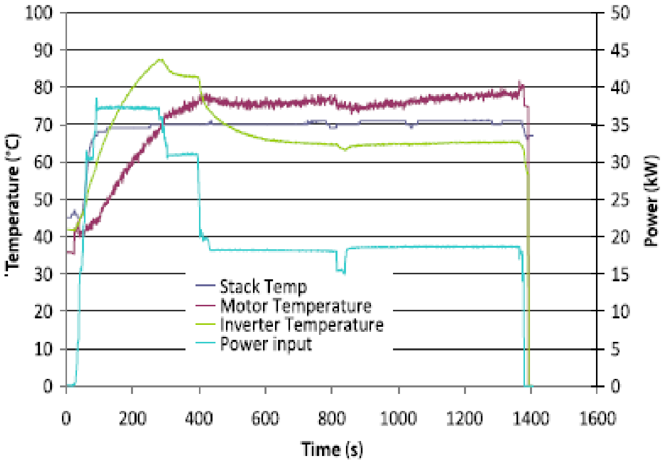

Fig. 11 Temperature profiles during a typical duty cycle.

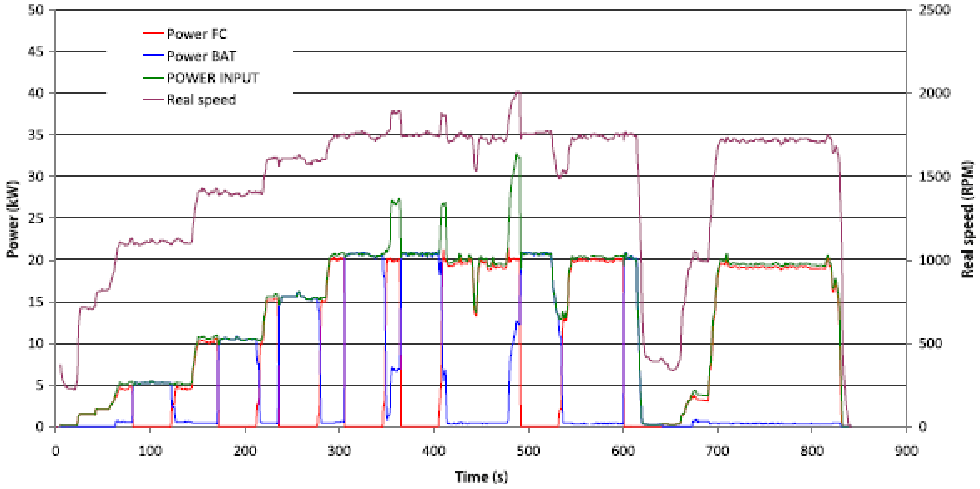

Fig. 12 "Power blending" ground test.

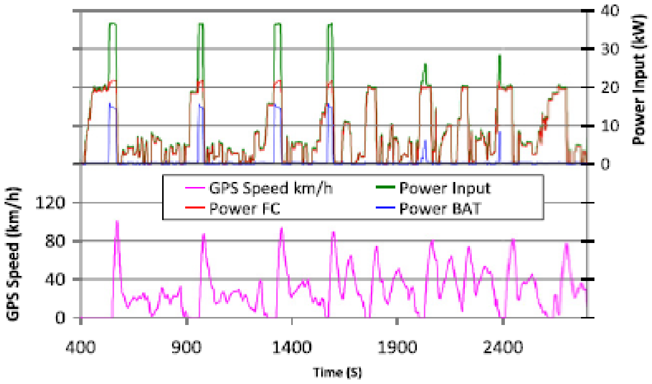

Fig. 13 Summary of the high speed roll-out powers and gps ground speed.

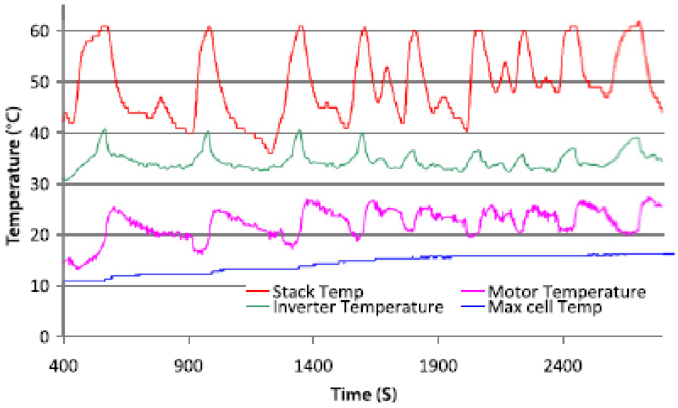

Fig. 14 Summary of the high speed roll-out temperatures.

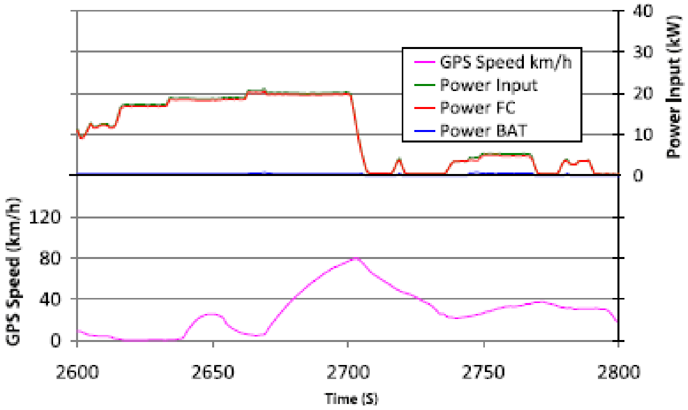

Fig. 15 Fuel cell alone take-off power and ground speed.

Fig. 16 RAPID-200 fuel cell in flight & the APL-S100 fueling station (http://www.enfica-fc.polito.it/).

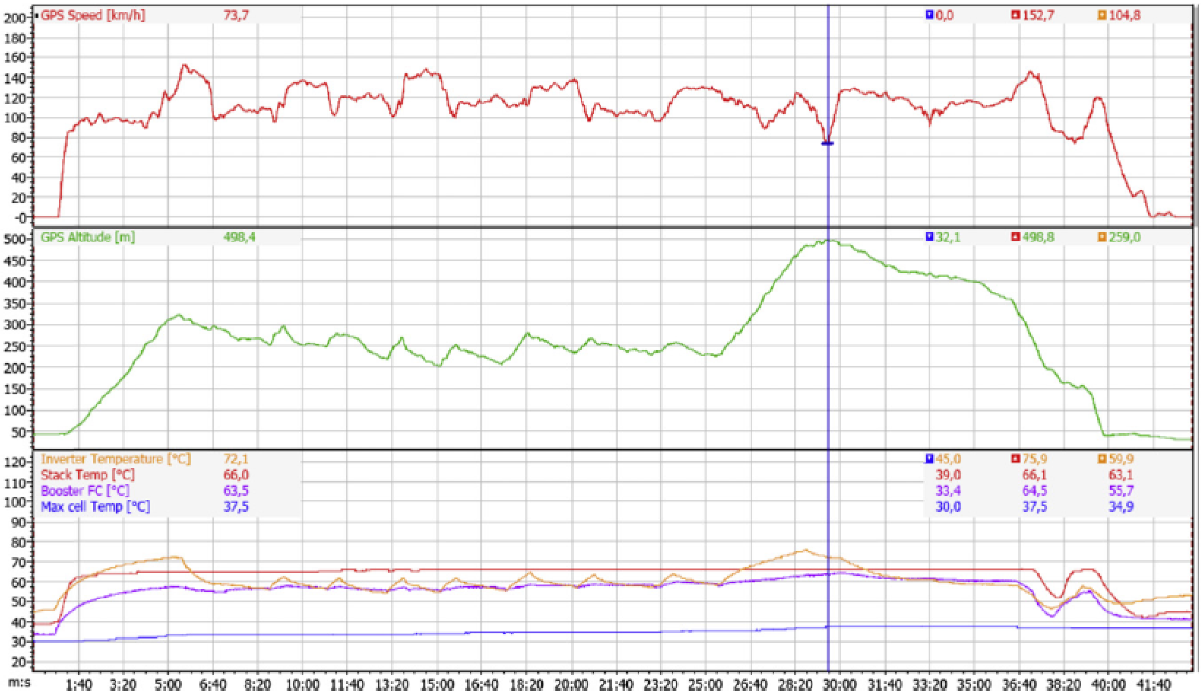

Fig. 17 Third mission flight data.

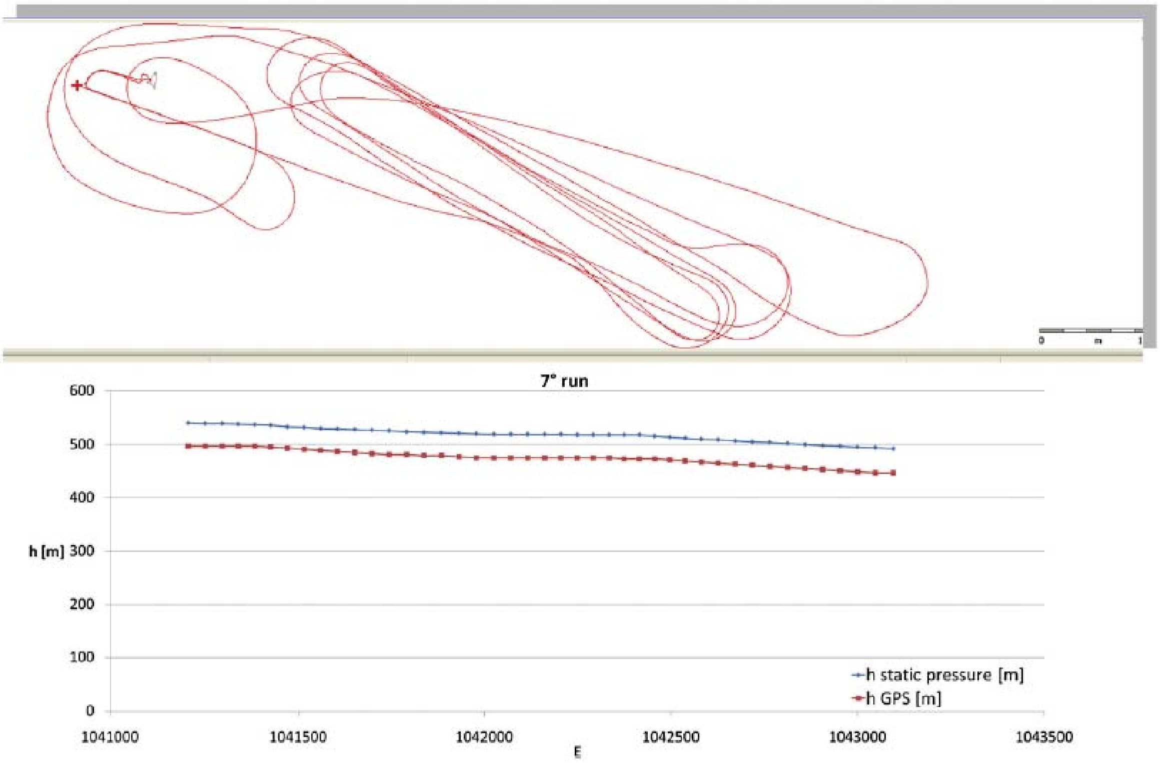

Fig. 18 Third mission flight path and altitude.

Table 1 Weights breakdown of power subsystems.

Component	Mass [kg]
Empty Aircraft [EA][a]	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][b]	75
TOTAL	554

[a] Aircraft operative empty weight minus engine weight. The estimated weight includes a modified engine mount (3 kg) and the new propeller (4 kg).

[b] The ENFICA-FC converted Rapid200 is designed for a single pilot.