JOURNAL OF AIRCRAFT
Vol. 48, No. 4, July–August 2011

Setup and Test Flights of All-Electric Two-Seater Aeroplane Powered by Fuel Cells

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DOI: 10.2514/1.C031271

The paper deals with the setting up and test flights of a fuel cell general aviation aircraft fuelled by hydrogen. 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 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. Six test flights were successfully carried out by Politecnico di Torino. The all-electrical power system was successfully tested during the 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 by means of only a fuel cell power setting. A new speed world record of 135 km/h and an endurance of 39 min were established during several flights conducted for the Federation Aeronautique Internationale sporting code category C (airplane). Two and a half hours of effective flight were obtained during these six tests for a total path of 237 km. The positive handling qualities and satisfactory engine performances of these six flight tests have led the team to consider these successful flights as a good starting point for further long endurance high-speed flights.

Introduction

THE hydrogen and fuel cell (FC) 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 onboard electrical systems in larger "more-electric" or "all-electric" aircraft.

Different studies were undertaken in recent years on FC in aeronautics ([1–3]). The Boeing Company [†] successfully flied the first fuel-cell-powered airplane in April 2008.[‡] The single engine propeller driven motor-glider Super-Dimona was modified by replacing its combustion engine with FCs and an electric motor. Boeing prototype flew for about 20 min at approximately 120 km/h. DLR, German Aerospace Center also flew in July 2009 with the motor-glider Antares powered by FCs.[§] In both cases, a motor-glider was used and is classified in Class D, according to Federation Aeronautique Internationale (FAI) sporting code ([4]).

The main objective of the ENFICA-FC project (Environmentally Friendly intercity Aircraft powered by Fuel Cells, a European Commission funded project coordinated by Giulio Romeo)[¶] [5,6] was to develop and validate the use of a FC-based power system for the propulsion of more/all-electric aircraft. The FC system was installed in a light sport aircraft RAPID 200, which was flight- and performance-tested as proof of the functionality and future applicability of this system for intercity aircraft.

The ENFICA-FC consortium consists of nine partners representing the whole chain of aircraft manufacturers (Israel Aerospace Industries, Evektor, and Jihlavan Airplanes), a FC Power system producer (Intelligent Energy, or IE), a hydrogen distributer (Air Product, or APL), research institutes (the Politecnico di Torino-Polito, the Université Libre de Bruxelles-ULB, and the University of Pisa-Unipi) as well as a company 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 intercity aircraft power systems that could be provided by FC technologies (auxiliary power unit, 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 fuelled by liquid hydrogen ([7,8]). 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 FC, was assembled and tested.

The high-efficiency, two-seater aircraft Rapid 200, manufactured by Jihlavan Aircraft (now Sky Leader), was selected for conversion from over more than 100 light sport aircraft through a multicriteria analysis performed by the Politecnico di Torino.

This paper concerns the activities related to the second aforementioned point. The first section concerns the main aspects of the conversion activity from a design point of view to provide an overview on system architecture and on the processes that lead to it. The following section concerns a more detailed presentation of the innovative power system broken down into its different subsystems. The last section presents results from experimental testing carried out during the project; results are related to three different levels of growing complexity: subsystems level, semi-integrated system level, and operative aircraft level.

Conversion Design

After the selection of the aircraft ([9]) an extensive conversion design activity was undertaken; the main properties of the selected aircraft (powered by an Internal Combustion Engine) are reported in Table 1.

Received 15 October 2010; revision received 24 January 2011; accepted for publication 17 February 2011.

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†The Boeing Research & Technology Centre, Madrid.

‡Additional data available at http://www.boeing.com/news/releases/2008/q2/080403a_nr.html [retrieved Jan. 2011].

§Additional data available at http://www.dlr.de/en/desktopdefault.aspx/tabid-1/86_read-18278/ [retrieved Jan. 2011].

¶Additional data available at http://www.enfica-fc.polito.it/ [retrieved Jan. 2011].

Table 1 Main characteristics of the RAPID 200-ICE

Maximum takeoff 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 h
Range	760–1050 km
Takeoff 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

Table 2 Converted aircraft mass breakdown

Component	Mass, kg
Empty aircraft [a]	221
Electrochemical subsystem	
Water management subsystem	103
Heat exchanger	
Control subsystem	
Pressurized hydrogen subsystem	51
Electric motor	38
ac/dc + dc/dc subsystem	14
Battery pack 1	26
Battery pack 2	26
Pilot [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.

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 mission can be summarized as follows: 1) takeoff; 2) climbing up to 1000 m with a climbing rate of 2.5 m/s; 3) cruising over the airport at approximately 150 km/h for 40 min; and 4) descending and landing.

The requested mission performances were based on a parametric study and system architecture design (see next section) that was conducted by the authors and is reported in [9]; 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.

A better understanding of the aerodynamic behavior of the aircraft was needed to define the power requested for the mission phases; a computational fluid dynamics (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 ([10]), which must guarantee a proper cooling of the different systems installed in the engine bay (see next section), 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.

The polar curves used for the computation of the required powers are reported in [11]. The required powers for each mission phase are shown in Fig. 1.

A particular architecture was adopted for the power system to obtain an aircraft that could fly the prescribed mission. Relying solely on FC for the entire mission, including takeoff, leads to an excessive weight due to the required large FC system at high power (40 kW); for this reason a hybrid battery/FC system was chosen (see the following sections for a complete description of the subsystems).

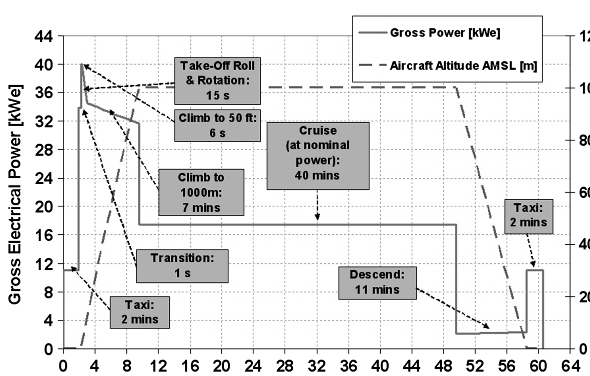

Fig. 1 Mission and requested gross power profiles.

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 (takeoff and climbing); the FC always work up to 20 kW, which is their maximum power output (approximately 50% of the power requested during takeoff) for all the flight phases (takeoff, 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 failure of FC. Although fuel cells were designed with an high level of reliability (mean time between failure = 5.000 hour) it was decided to install a power backup system to allow the pilot to land safely.

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

The installment of the new power system represented a very important step from the design point of view. The conventional power system that the aircraft structure was designed for is very different from the FC one, both because of the number of items and the volumes of these items; above all, the balance of the aircraft had to be maintained, bearing in mind the safety constraints that are particularly important when operating with high pressure hydrogen. An extensive study of the optimum layout was reported in [9]. The weights of subsystems are reported in Table 2 and the final configuration is shown in Fig. 2.

Some structural components had to be redesigned or introduced to make the new layout possible. The engine mount was carefully and extensively redesigned to support the many different subsystems; a special lightweight support plate was designed for the hydrogen tanks; this plate meets the high acceleration requirements (9 g) requested by European Aviation Safety Agency: Very Light Airplane (EASA/VLA) regulations for items that can hit a pilot during a crash landing.

Since the weight and available power of the converted aircraft are very different from the conventional one, as is the behavior of the engine, a new propeller was designed, manufactured and tested.

The aircraft was equipped with a data acquisition system (Enclosed Dash Logger MOTEC-EDL2) that measures and records

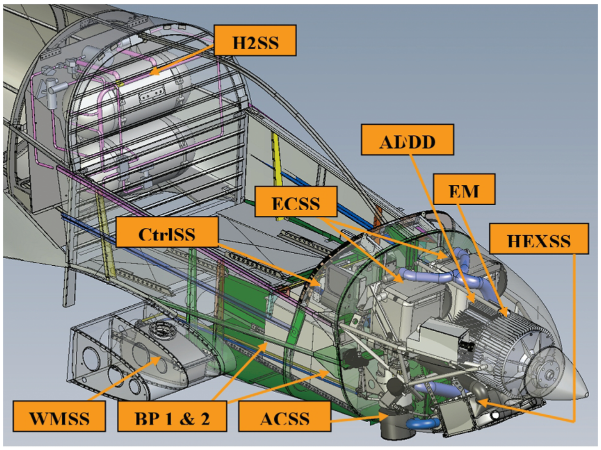

Fig. 2 Final layout configuration.

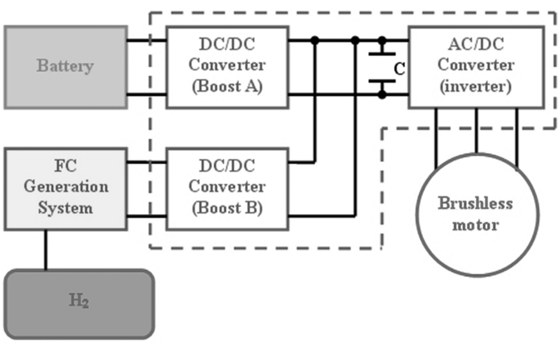

Fig. 3 Power system schematic.

important vehicle parameters (more than 50) via the general CAN-bus used in all onboard devices for communication purposes. The data is sent by an onboard radio transmitter (Satel Radio) to a radio receiver in the ground control station, and this allows the test engineers to monitor, save, and postprocess data while the aircraft is flying its mission. This increases the chance detecting any possible system malfunctions.

Power System Description

This section presents an overview of the main features and performances of each subsystem that contributed to generate flight power. A schematic of the power system is reported in Fig. 3.

The engine is a brushless electric motor produced by Phase Motion Control; the main features are reported in Table 3. The brushless motor was chosen by the first author, at the beginning of the project, to guarantee the necessary performance; 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.

Table 3 Brushless motor main features

Motor type	PMSM frameless
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 and torque	92 kW
Maximum service temp	120°C

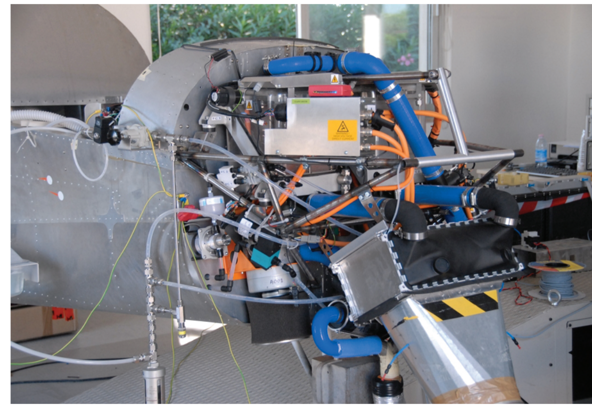

Fig. 4 Fuel cell system assembled in the mockup fuselage.

The FC system (developed by IE), which is able to provide 20 kW of net unregulated power, consists of: 1) A FC stack and electrochemical system, 2) a heat exchanger system, 3) an air delivery and water recovery system, 4) a water management subsystem, and 5) an electrical and electronic support system and a control and internal battery subsystem.

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

The electrochemical subsystem (ECSS) consists of two separate FC units. To provide a safe mounting system, the FC 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 subsystem (ACSS) was designed as two-stage centrifugal compressors in series. This system brings fresh air from the engine cowling inlet and feeds FC 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 FC 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 reused. The water management subsystem (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 subsystem (CtrlSS) comprises an FCS central communication and control module and an internal battery subsystem (a battery that is used to start up the FC).

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 liters each and they were manufactured for a working pressure of 350 bar (leading to a total H2 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 H2 leakage into the cabin. The tanks were secured with brackets mounted onto a lightweight construction that 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 to ensure that the hydrogen flowing from the tanks to the FC crosses the

Fig. 5 Hydrogen storage system.

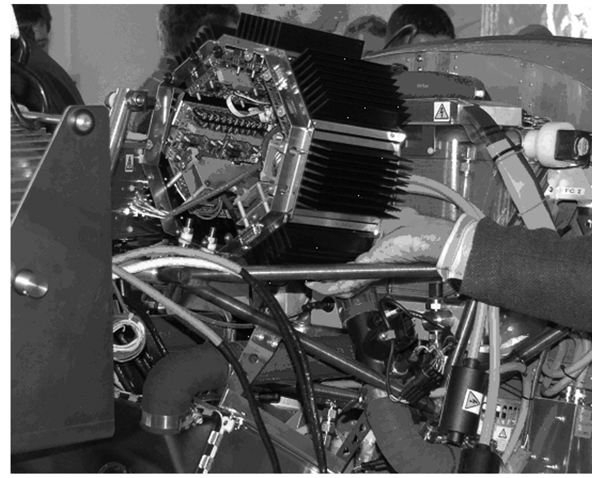

Fig. 6 Integrated vehicle controller.

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 (overpressure and overtemperature).

Two Li-Po battery packs supply the additional energy that is necessary for takeoff and climbing; packs are able to deliver 20 kW for about 18 min. They are stored in two carbon fiber containers (with glass/fiber covers) which are secured with rails to the cabin floor on the copilot'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. The batteries were manufactured by Air Energy for Politecnico di Torino and present features reported in Table 4.

The presence of two different power sources and the will to fly relying only on FCs as much as possible, without compromising safety, led to the necessity of properly managing interaction between the FC and the battery pack. As shown in Fig. 3, 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 does not allow correct selection. The purpose of the inverter is to properly modulate the direct current bus coming from the boosters 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 system, designed and produced by Maver srl for the ENFICA-FC project is very compact, very efficient (>97%) and very light (14 kg) (Fig. 6).

Testing the System

Several experimental testing activities were performed at different levels of integration. Initially, the manufacturers or suppliers of each subsystem provided test results on their own systems; then an intermediate test campaign was carried on a semi-integrated fuselage mockup 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.

Table 4 Batteries main features

Type of cells	Lithium polymer
Nom. voltage	207.2 V
Nom. capacity	30 Ah
Nom.energy	6.2 kWh
Energy at 20 kW, 20°C	5.8 kWh
EOC voltage	235 V
EOD voltage	185 V
Min power 15 min, required	20 kW
Cell weight	48 kg
Weight incl. case and BMS	51 kg with CFRP case
Dimensions	2 modules 220 ∗ 300 ∗ 300 mm
Charge time with 3 kW charger	3 kW/220 V-50 Hz, 240 V 12 A

Individual Subsystem Testing

Since the FC 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 ([12]).

The battery system is technologically more developed and so more reliable than the FC 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 cutoff (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 cutoff, 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, to land during a FC 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

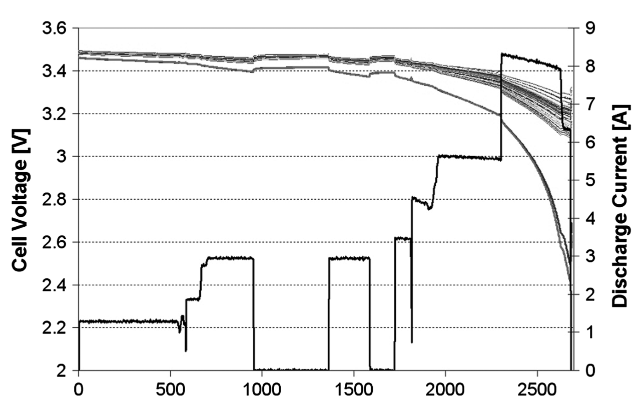

Fig. 7 Battery packs anomalous discharge.

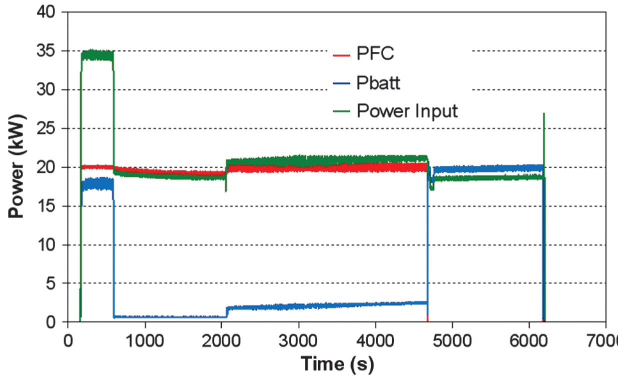

Fig. 8 Power profiles during an extended duty cycle power electronics test.

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 as follows ([10]):

1) At the very beginning of the takeoff phase, because of the maximum power in conjunction with the low speed, and there is therefore limited cooling for a short period.

2) 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 the 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 Economic Commission for Europe 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.

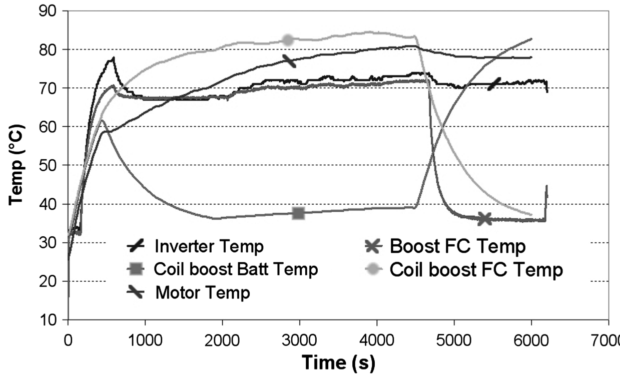

Fig. 9 Temperature profiles during an extended duty cycle power electronics test.

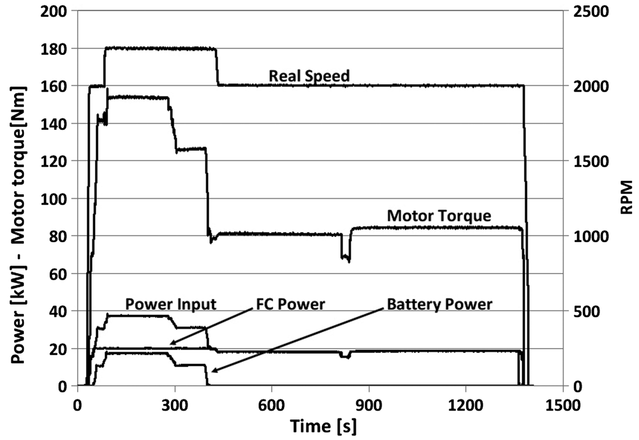

Fig. 10 Power, torque, and rotations per minute profiles during a typical duty cycle.

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 FC system in its final configuration, was completely installed on a fuselage mock-up (Fig. 4) 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 derated 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 FC. Moreover, as the FC 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 Fig. 10 and 11 for one of the final tests, where the system was basically ready for final installation.

Testing of the Integrated System

The final and most extensive test campaign was devoted to the complete aircraft (Fig. 12); 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.

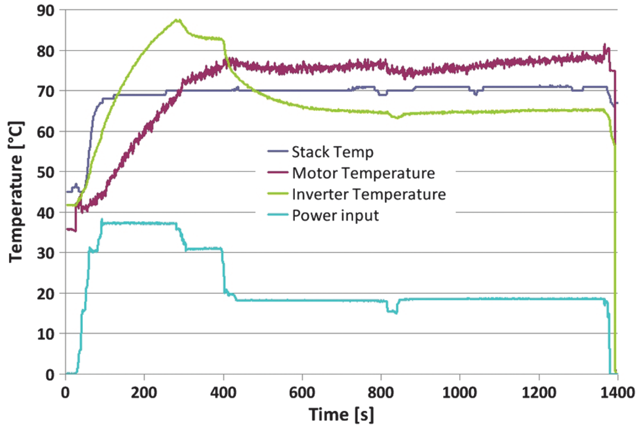

Fig. 11 Temperature profiles during a typical duty cycle.

Fig. 12 RAPID-200.

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 takeoff and cruising. Again great attention was paid to correct the handling of the two onboard power sources; a simulation of FC failure is reported as an example in Fig. 13.

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 FC (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 FC cannot provide the requested power, the system

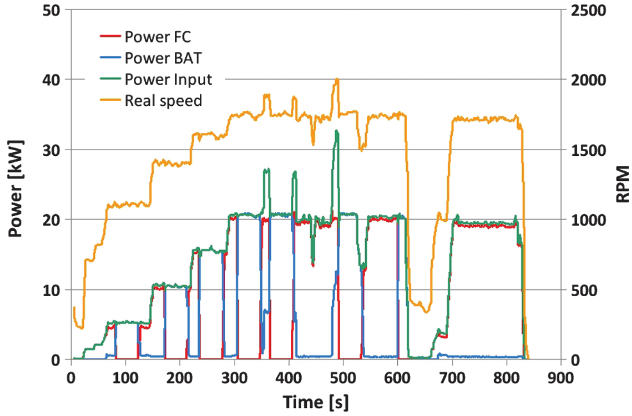

Fig. 13 "Power blending" ground test.

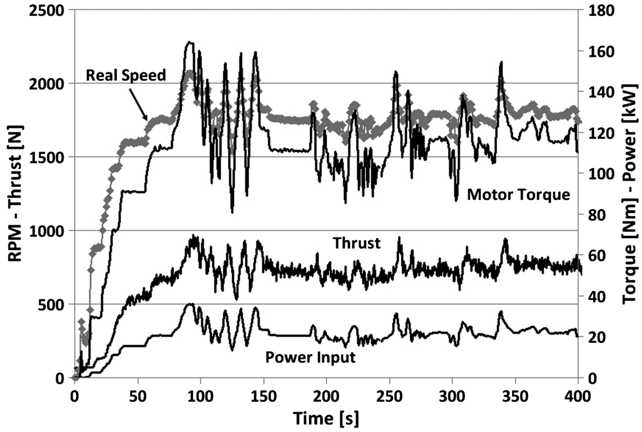

Fig. 14 Test results of the two-blade propeller.

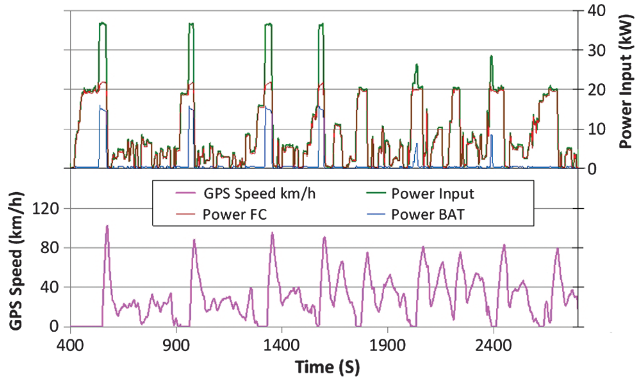

Fig. 15 Summary of the high-speed rollout powers and GPS ground speed.

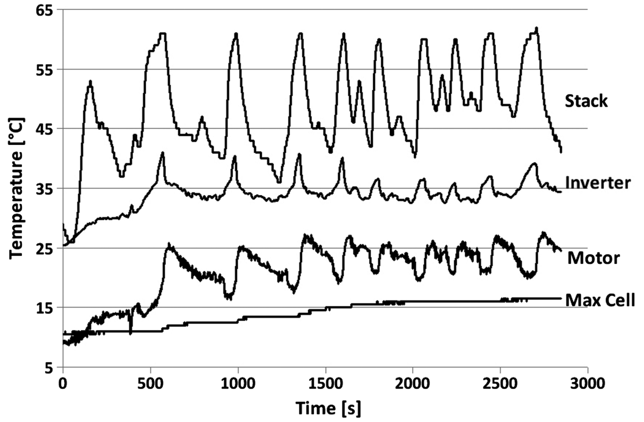

Fig. 16 Summary of the high-speed rollout temperatures.

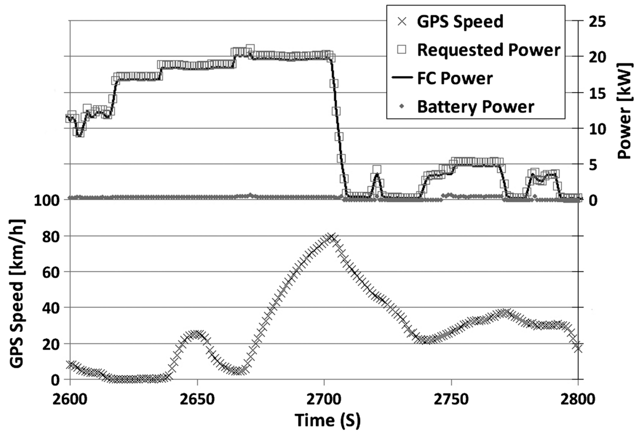

Fig. 17 Fuel cell takeoff power and ground speed.

Fig. 18 The S100 fueling system.

immediately demands power from the battery, but the performance of the motor does not change. Moreover, the system tries to recover the FC from its inoperative state and, if successful, to reestablish the FC 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.

Two different propellers were tested other than the one designed for the converted aircraft; in particular, a commercial ground variable pitch three-blade propeller was tested as an alternative solution to the two-blade one designed by the Politecnico di Torino. The test results for the two-blade propeller are shown in Fig. 14; this is the propeller that was finally installed and used for the flights. The choice of the propeller for this particular aircraft is more problematic than for 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 in the current it can handle. This has a consequence on the propeller, which needs to work with a relatively high rpm to absorb the available power; if this were not the case, the

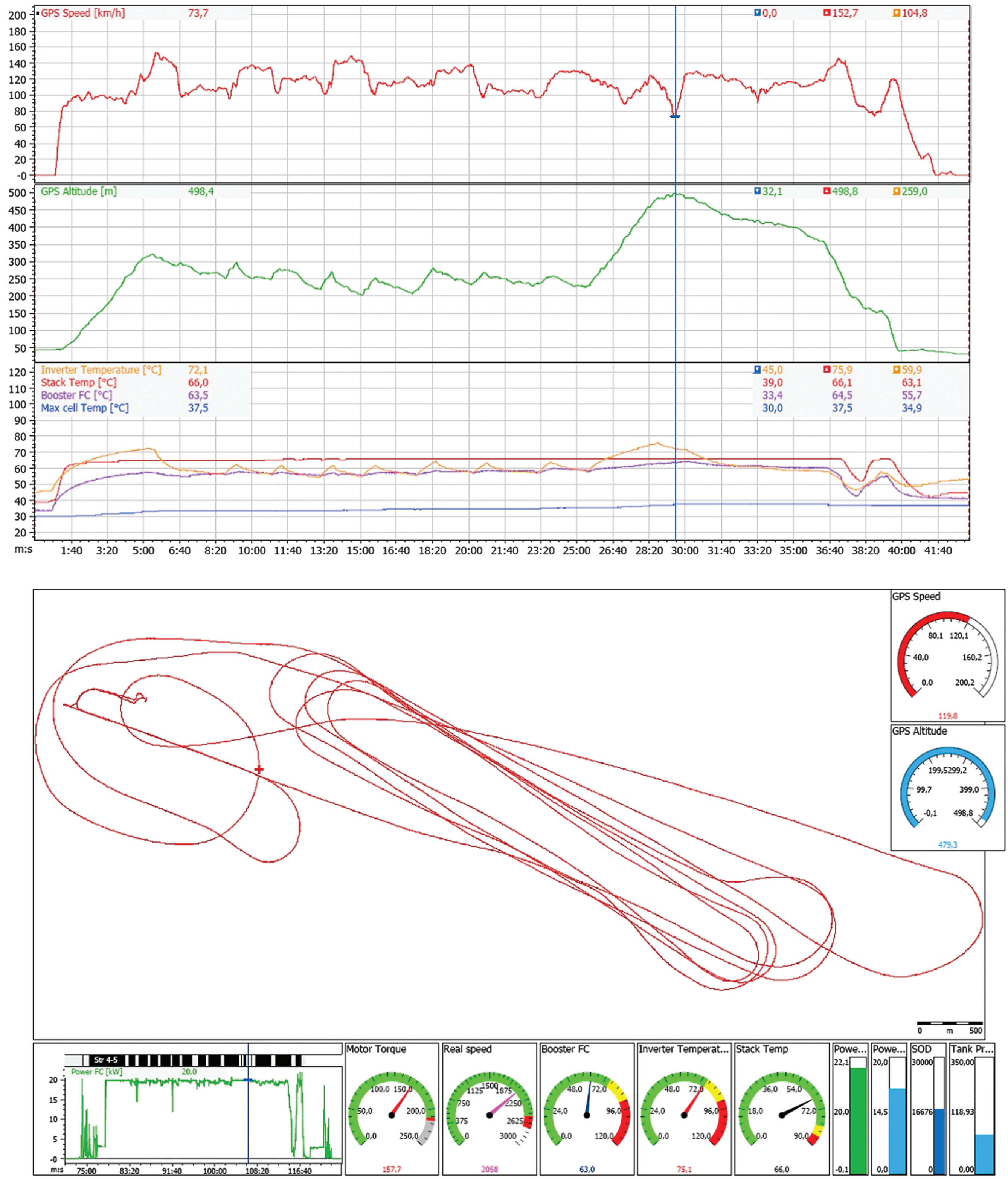

Fig. 19 Third mission flight data.

system would be able to develop more power than the amount it can effectively use to generate thrust.

As mentioned above, having the complete system installed allowed to be checked for the first time the real efficiency of the cooling systems (FC, motor, and power electronics). To investigate this aspect, the temperatures were observed during high-speed rollouts, which were performed to test the theoretical data pertaining to the takeoff distances and speeds (Fig. 15).

As shown in Fig. 16, the cooling systems showed very satisfactory behavior, and the temperatures were kept below the admissible limits (the external temperature was 19°C).

To investigate the potential performances of the system for future developments, it was decided to check takeoff without battery support. The aircraft was accelerated up to rotation speed (80 km/h) and, for safety reasons, the takeoff was aborted before the climbing phase started (Fig. 17). It was possible to reach the rotation speed in

Fig. 20 Fifth mission flight data.

350 m (180 m is the usual distance when 35 kW of power is supplied by both FCs and battery), but further testing should be carried out for the climbing phase to be sure that the aircraft can effectively run entirely on FC power, and careful considerations have to be made on reliability before completely removing the batteries from the system.

Flight Tests

After the extensive test campaign, the aircraft was finally flown at Reggio Emilia airport. Six flights were performed, first with a 2 min maiden flight and ending up with the world speed record for electric aircraft powered by FCs, according to a draft FAI sporting code, being broken.

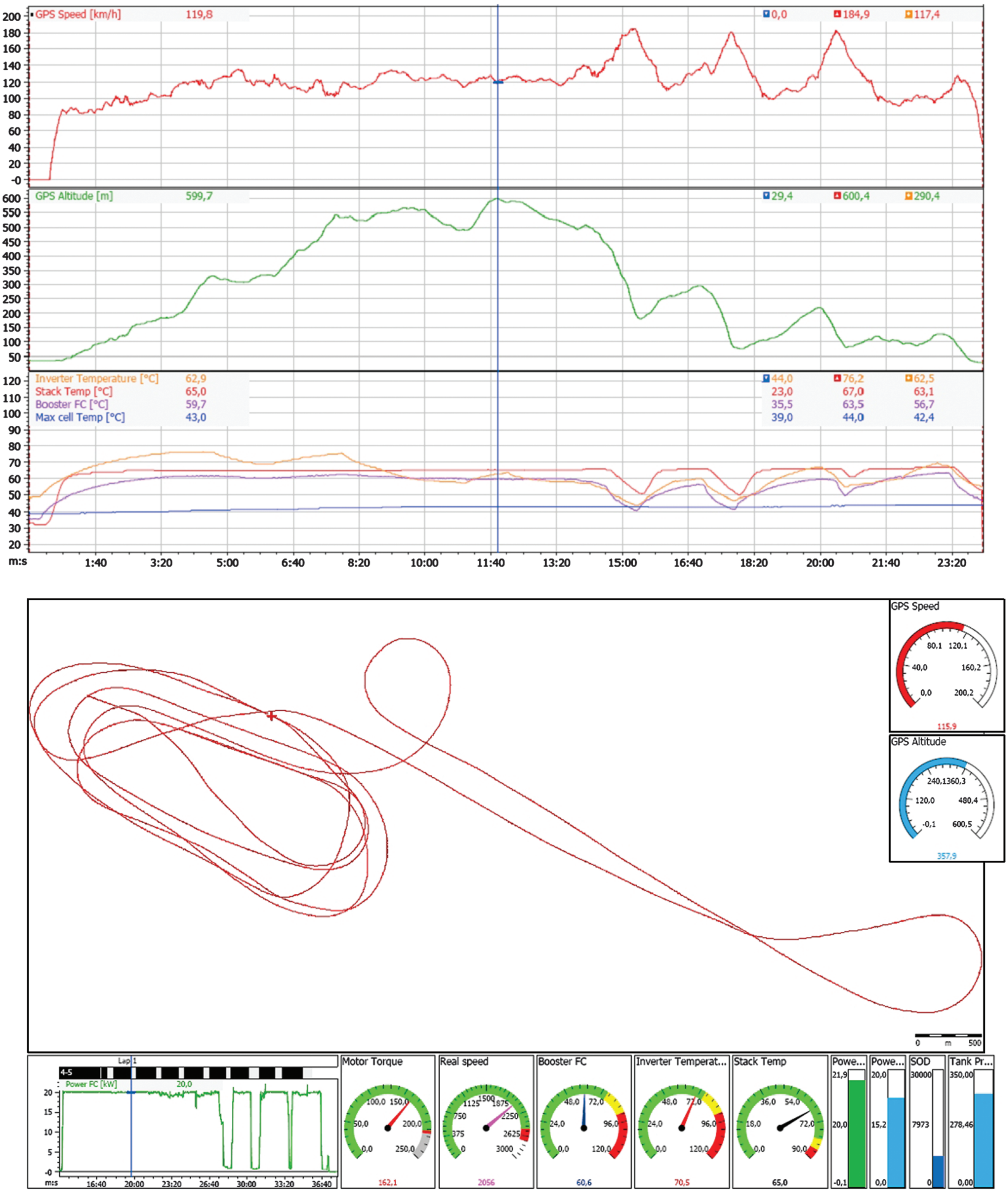

Fig. 21 Sixth mission flight data.

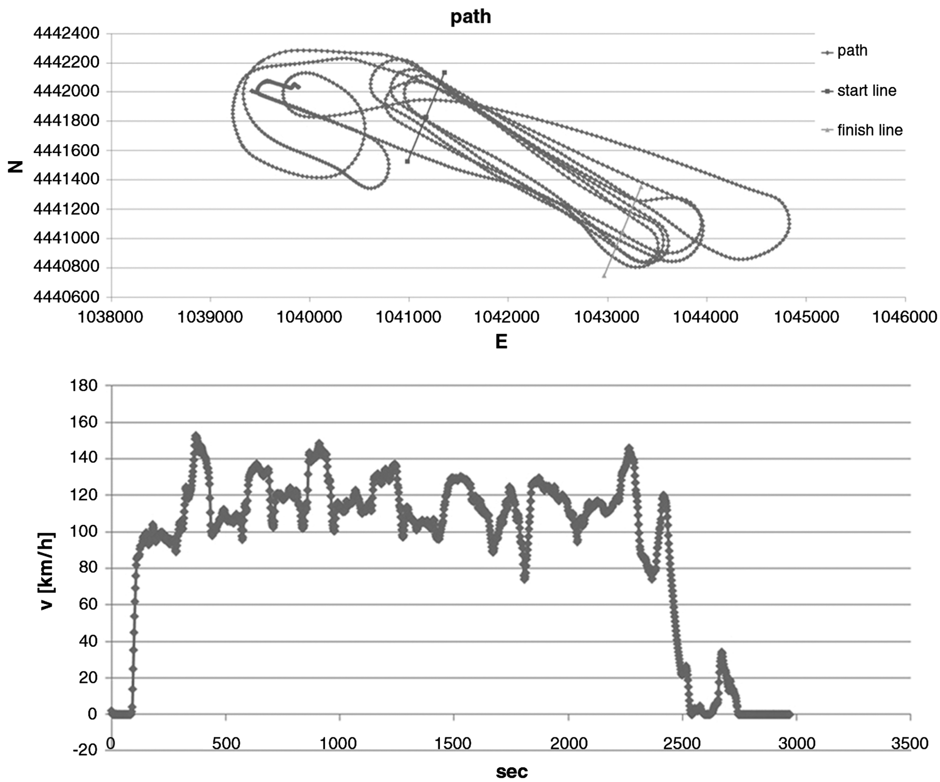

Fig. 22 Flight path and ground velocity of flight 3.

The 350 bar APL S100 hydrogen refuelling system was installed at the Reggio Emilia airfield for these tests. An overall view of the system is given in Fig. 18.

The complete system is composed of: 1) a hydrogen pack (16 bottles at 200 bar), 2) an air compressor to increase (through a membrane) the hydrogen pressure to 420 bar in the refueling station, 3) a safety system (flame detection + H2 leakage + automatically stop), and 4) the S100 refueling station.

Six flights were performed and the telemetry-recorded flight data for missions 3, 5, and 6 are reported in Figs. 19–22 as these were the most significant flights in terms of endurance. 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 was 40 min (as shown in Figs. 19 and 20), the limiting factor not being the hydrogen, as expected, but the water consumption. The capacity of the water tank (8 liters) is undersized, and this will be optimized in a future development. Mission 6 was terminated after 23 min because of a change in the atmospheric conditions, which could have led to unsafe operations.

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 Global Positioning System (GPS) data logger (LX Navigation Colibrì) was also installed onboard 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 (Fig. 22).

The main results obtained during flights 3 and 5 were as follows:

1) A maximum endurance of 39 min was recorded.

2) A maximum speed of 135 km/h was recorded during runs 6–7.

3) A greater maximum speed than 158 km/h was reached during a free flight.

4) 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.

5) A minimum value of the water level of about 15% was reached.

6) The total GPS horizontal path length (taxi + rollout + climb+ horizontal flight + landing) was 76,500 km.

Conclusions

The extensive experimental campaign carried out during the ENFICA-FC project, as well as the theoretical estimations, have proven that FC 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 Company in their first hydrogen flight (120 km/h for 20 min, but for a motor-glider, class D, FAI sporting code); DLR, German Aerospace Center also flew in 2009, but with a motor-glider (class D, FAI Sporting Code) powered by FCs.

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, FCs and the related technologies seem to need improvement from the gravimetric efficiency point of view; for example, the hydrogen storage system, which weighs 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, as far as both flights (speed, endurance) and payload capability are concerned (it was impossible to carry a second pilot/passenger in the converted aircraft). A midrange development would be sufficient to obtain performances that could be compared with those of a modern general aviation aircraft.

The real strength of the “all-electric aircraft” concept does not lie in an improvement in the performances, but in the environmentally friendly use of the aircraft itself; such an aircraft could be used in airports surrounded by urban centers, during the night, and in environments that are restricted because of excessive pollution risk.

Acknowledgments

The authors acknowledge the important contribution made by the European Commission funding the ENFICA-FC, EC 6th FP programme, Contract No. AST5-CT-2006-030779 (2006-2010). The authors also acknowledge the contribution of the Consortium partners.

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