LONG DISTANCE FLIGHT TESTING WITH THE FUEL CELL POWERED AIRCRAFT ANTARES DLR-H2

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Abstract

The Institute of Technical Thermodynamics of the German Aerospace Center has been conducting research on fuel cell systems for aircraft applications for several years.
Fuel cell systems provide an interesting possibility of power generation on board of wide-bodied aircraft. The by-products of fuel cell on-board operation are water, heat and oxygen depleted air. These can be harnessed, resulting in savings of resources and reduction of overall system take-off weight.
For the development of operation strategies for these systems realistic testing under aeronautic conditions is necessary. This can be performed by means of the flying test bed Antares DLR-H2. This all-electric motor glider features two payload nacelles which can be equipped either with high energy lithium-ion-accumulators or a low temperature PEM[1] fuel cell system and a hydrogen pressure tank.
The integration of the next generation fuel cell system has been completed in August 2012. In September 2012 long distance flight testing with the fuel cell system has been performed.
In this paper the system architecture of the next generation fuel cell systems will be drafted. Furthermore the findings and measurements of the long distance flights will be presented. Finally conclusions drawn from the results will be outlined.

1. INTRODUCTION

Fuel cells provide a promising technology for highly efficient conversion of the energy chemically stored in hydrogen into electrical energy. But not only the electrical energy produced by the fuel cell may be utilized but also waste heat, product water and oxygen depleted air can be valuable resources. This multifunctional approach makes fuel cell systems especially interesting for aircraft applications, which is discussed in [1].
Testing for aeronautical fuel cell applications may be accomplished in laboratory environments. But simulating all the ambient conditions, such as low pressure and low temperature combined with the occurring accelerations during flight, is hard to achieve. Therefore the research fuel cell powered aircraft Antares DLR-H2 has been developed.

2. GENERAL INFORMATION ON THE RESEARCH AIRCRAFT

The Antares DLR-H2 is a research aircraft based on a serial produced electrically powered motor glider. In the serial version the energy for the electric drive chain is provided by high-energy batteries located in the wings. The Antares DLR-H2 has been equipped with two payload nacelles as shown in Figure 1. Each payload nacelle, also called pod, may have a maximum weight of 135kg (including surrounding structure). Currently two sets of pods are available for research purposes. The first set comprises two pods with high-energy lithium-ion batteries, which triple the overall energy content of the battery system to allow flight durations of more than two hours.

Figure 1. Antares DLR-H2 with payload nacelles

The second set of pods consists of a hydrogen storage tank pod (installed on the right hand side) and a fuel cell pod (installed on the left hand side).
The tank pod contains a 350bar tank system which is capable of storing up to 4.9kg of compressed gaseous hydrogen. However due to the nature of the pressure regulator the hydrogen in the tank cannot be depleted completely during operation. Furthermore a reserve for five minutes of fuel cell operation has to be provisioned so that at 40bar residual pressure the tank has to be considered to be empty. A standard tanking nozzle from automotive industry assures compatibility with 350bar hydrogen fuel stations. Tank pressure, fuel line pressure, tank surface temperature and internal pod temperature are monitored and logged by a data acquisition system.
The fuel cell pod contains a fuel cell system consisting of 3 modules electrically connected in series, thus providing a nominal output power of 30kW. The main parasitic loads, as the impeller for cooling air supply and the blowers for cathode air supply, have been designed as high voltage components running directly from fuel cell system voltage. This avoids a large part of losses due to efficiencies of the DC/DC-converters and additional weight for the converter modules themselves. Measurements provided by the

[1] polymer electrolyte membrane

sensors of the fuel cell system and the peripheral components are recorded in an analogous manner as done in the tank pod. Furthermore measurements of the battery system and the electric drive chain are logged.
Hydrogen security is achieved by six sensors which are located in all critical areas of the plane: tank pod, fuel cell pod and fuselage. They are arranged in pairs to accomplish redundancy. The fuselage is monitored because the hydrogen supply line traverses the fuselage on its way from the tank system to the fuel cell system.

3. LONG RANGE FLIGHT TESTING RESULTS

In summer 2012 the new generation low temperature PEM fuel cell system had been integrated. In September 2012 long distance flight testing had been performed to study the performance of the system and to identify potential for future optimization.
Within this flight campaign six single flights have been accomplished: to local flight in Zweibrücken and Stuttgart and four cross-country flights: Zweibrücken (Rhineland-Palatinate) – Hof (Bavaria), Hof – Berlin, Berlin – Hof and Hof – Stuttgart (Baden-Württemberg).
In the following results from the long range flight tests are presented. Section 3.1 has a focus on overall system performance of a three-module-combination whereas section 3.2 looks at the performance of single fuel cell modules.

3.1. Influence of altitude on fuel cell performance

In the following the performed flights have been analyzed to determine the influence of flight altitude on fuel cell performance. Therefore flight measurements are compared with measurements from ground tests. To obtain comparable results it is important that the measurements are subject to the same boundary conditions except for the difference in altitude. In the different measurements following conditions have to be fulfilled:

- The working point under consideration has to be the same in flight and ground measurements.
- The load current has to be constant in the time period under consideration to have stable conditions in the fuel cell system.
- In the time period under consideration the altitude has to be as constant as possible.
- The temperature of the fuel cell system on ground and during flight has to be the same, since operating temperature has a major impact on fuel cell performance.

Only two test flights meet these boundary conditions: Zweibrücken – Hof (2012-09-08) and Hof – Berlin (2012-09-09). Since both flights have been performed at the same altitude only the track Hof – Berlin has been selected for further examination. Figure 2 illustrates load current and altitude during this flight which features a comparatively constant flight level. The vertical lines mark a corridor with a flight altitude of 1545m±60m (measured by GPS). In this given timeframe not only the altitude but also the load current are relatively constant, so within these constraints the mean values of system current, system voltage, system temperature and altitude have been calculated (see Table 1).

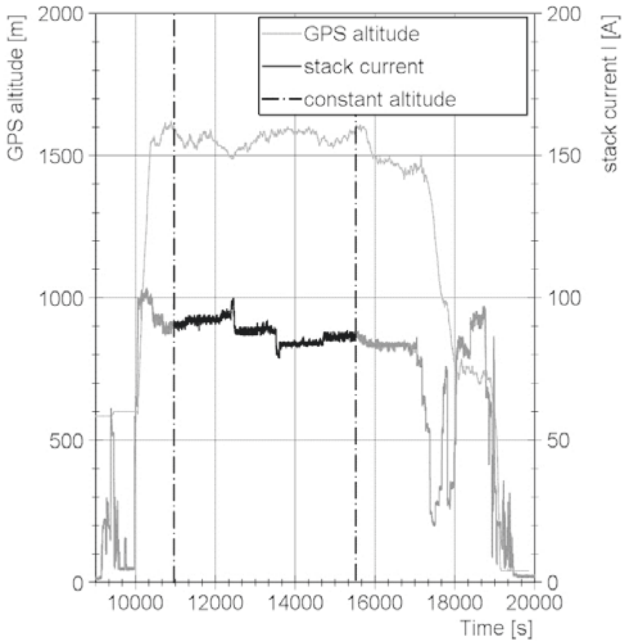

Figure 2 System current and flight altitude vs. time (flight Hof - Berlin)

The results of two ground tests are used to draw a comparison:

- Figure 3 shows the initial start-up after completion of the system integration. The load had been gradually increased until reaching maximum test load current.
- Figure 4 shows a load cycling test. The first load cycle has been applied to the cold system whereas the system is already heated up when the second load cycle is applied.

These tests have been conducted consecutively on ground before flight in Zweibrücken at an altitude of 350m (GPS value).
From both ground tests working points comparable to the flight test have been selected (see circle mark in Figure 3 and Figure 4) and the mean values have been calculated accordingly (see Table 1). Due to the dynamic loads in the ground test there are no extended periods of time with constant currents, especially in the load cycling test.

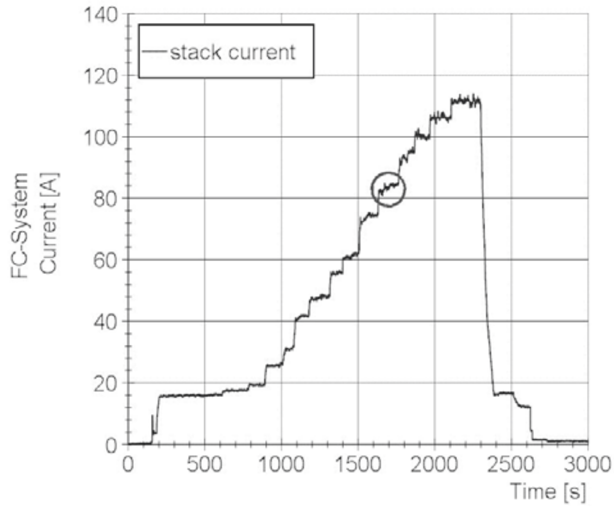

Figure 3 Initial start-up test

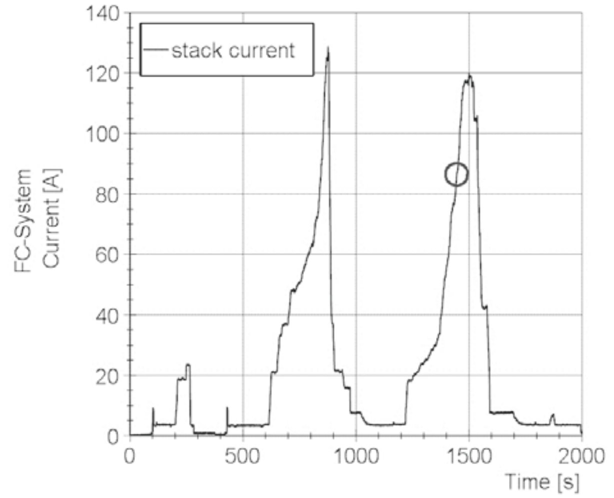

Figure 4 Load cycling test

Table 1 Comparison between flight and ground tests

	System Current [A]	System Temperature [°C]	System Voltage [V]	Altitude [m]
2012-09-05 (start-up)	83.5	55,3	208,1	350
2012-09-05 (load cycling)	87.5	52.4	206,7	350
2012-09-09 (flight test)	87.5	56.9	198,5	1545

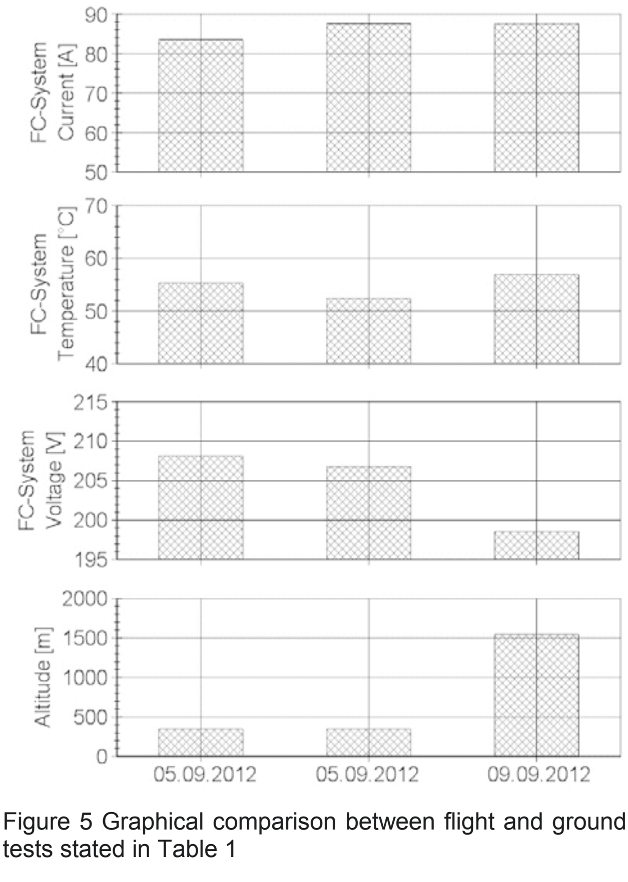

Figure 5 Graphical comparison between flight and ground tests stated in Table 1

The load cycling tests consists of two rising and two falling slopes. Only the second rising slope is taken into account for analysis, because

- the system underperforms on the first rising slope due to the cold start conditions and
- the system overperforms on the falling slopes due to the higher temperatures caused by the previous higher loads.

Table 1 and Figure 5 sum up the results from the two ground and the flight test. Although mean load current and mean fuel cell temperature are approximately equal fuel cell system performance is significantly decreased.

The difference between flight and ground test amounts to 1200m. The voltage drop of the overall fuel cell *system* accounts for about 9V or 4% relative to system voltage on the ground.

3.2. Comparison between anode recirculation and dead-end operation

In this section the same data will be analyzed as in section 3.1 but under different aspect. Here the focus lies on the performance of single fuel cell modules.
During flight the individual modules (electrically connected in series) had been operated in different hydrogen supply strategies. Modules #1 and #2 operated in recirculation mode where the anode gas from the outlet has been fed back into the anode input. This facilitates humidification of the membrane and increases the hydrogen utilization rate and thereby the efficiency [2]. The periodical purge of the circuit prevents the accumulation of inert gases and product water.
Module #3 had been operated in dead-end configuration where there is no constant flow-through in the anode bulk. The fed hydrogen remains in the anode bulk until consumption without forced convection. Inert gases and product water are purged from the anode bulk in regular intervals.
In the following only module #1 and #3 will be taken into account since module #2 essentially shows the same behavior as module #1.
Figure 6 shows the course of current and voltage of module #1 and #3 during the flight from Hof to Berlin (2012-09-09).
The lower diagram shows the stack current of the modules, which is the same for all three, since all modules are electrically connected in series. The initial peak in the current curve shows the ground test and pre-heating of the system and taxiing prior to the start. Looking at the upper diagram it is obvious that module #3 (light gray), which operates in dead-end mode, provides lower stack voltage than module #1 (black), which operates in recirculation at the same load current during the flight phase.
To quantify the difference between recirculation and dead-end the currents between 80A and 100A are taken into account, since these measurements represent relatively stable conditions during level flight. The transient current changes during start-up and landing are too short-lived to give reliable results. As marked in the lower diagram of Figure 6 three time frames have been selected. In every time frame the data had been filtered with respect to a current range:

- I: 8100s – 10200s, filter current range 93A±2A
- II: 10200s – 11300s, filter current range 88A±2A
- III: 11300s – 15000s, filter current range 85A±2A

Data not lying in this current corridor had been omitted. Mean values of the data belonging to the corresponding range (stack current, stack voltage, stack temperature, GPS altitude) have been calculated. The upper half of Table 2 contains these values.

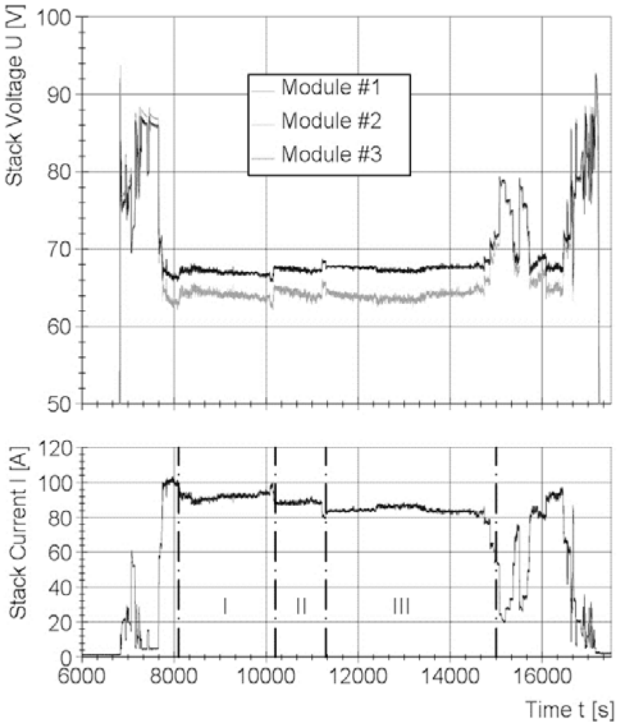

Figure 6 Stack current and stack voltage during flight

The flight measurements are compared to the ground test values from the initial start-up test already mentioned in section 3.1 and Figure 3. From the initial start-up data the following current ranges have been selected:

- a: filter current range 83A±1A
- b: filter current range 93A±1A
- c: filter current range 99A±1A

The calculated mean values can be found in the lower half of Table 2. The selected areas a, b and c are illustrated in Figure 7. Since the ground test measurements are subject to less noise than the in-flight recordings a current corridor of ±1A is used for mean value calculation.

In the indicated current ranges in Table 2 the arithmetic mean values of stack voltage, stack current, stack temperature and GPS altitude have been calculated for Stack #1 (operating in recirculation mode) and stack #3 (operating in dead-end mode). The last two columns show the calculated voltage decrease of dead-end operation with respect to recirculation operation as absolute value and as relative value with respect to the stack voltage in recirculation mode.

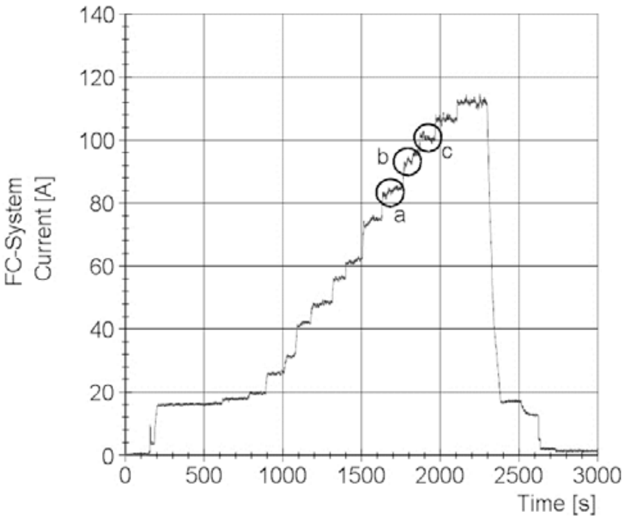

Figure 7 Initial start-up test with marked current ranges for comparison with flight test

Table 2 Mean values of current ranges I through III as indicated in Figure 6 and the current ranges a through c in Figure 7

Stack mode	Current range	Stack current	Stack voltage	Stack temperature	GPS altitude	ΔU Flight (abs) Rec. – DE	ΔU Flug (rel) Rez - DE
	[A]	[A]	[V]	[°C]	[m]	[V]	[%]
Flight Hof – Berlin (2012-09-09)							
Rec.*	85±2 (I)	84,45	67,52	56,26	1439	-	-
	88±2 (II)	88,41	67,37	57,12	1443	-	-
	93±2 (III)	92,55	66,89	57,4	1440	-	-
DE*	85±2 (I)	84,74	63,82	56,26	1439	-3,7	-5,5
	88±2 (II)	87,72	64,31	57,12	1443	-3,06	-4,5
	93±2 (III)	92,11	63,93	57,4	1440	-2,96	-4,4
Initial start-up test (2012-09-05)							
Rec.*	83±1 (a)	83,08	70,6	54,92	350	-	-
	93±1 (b)	93,06	69,4	56,91	350	-	-
	99±1 (c)	99,67	68,77	59,1	350	-	-
DE*	83±1 (a)	83,05	67,68	54,92	350	-2,92	-4,1
	93±1 (b)	93,04	65,44	56,91	350	-3,96	-5,7
	99±1 (c)	99,56	64,81	59,1	350	-3,96	-5,8

* Rec. = recirculation, DE = dead-end

Figure 8 illustrates the values given in Table 2. Black lines indicate in-flight measurements whereas gray lines represent ground test data. In addition in the upper diagram it is distinguished between recirculation (continuous line) and dead-end operation (dashed line).
In contrast to section 3.1 not only one load current value but a load current range of 83..99A has been considered. Depending on the ambient conditions these currents occur during level flight.

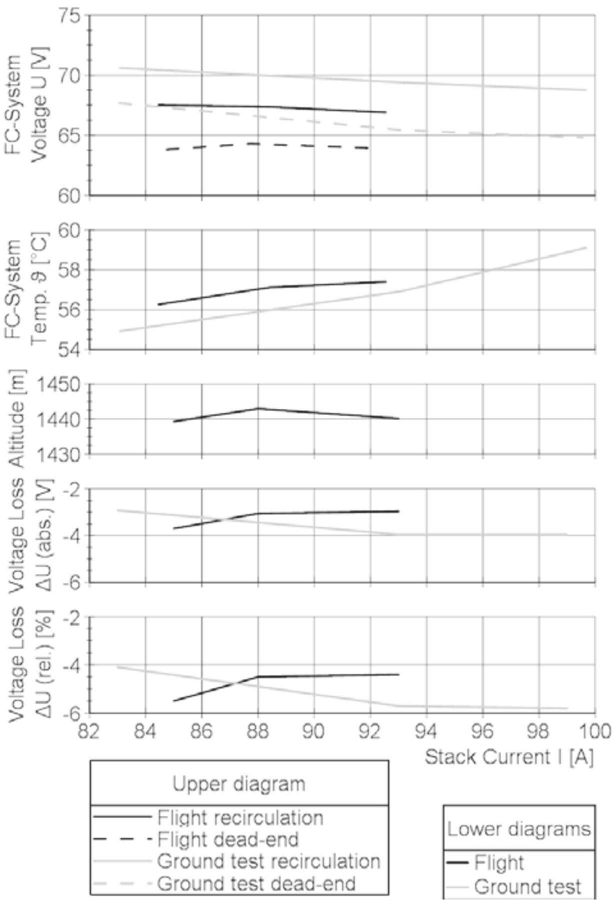

Figure 8 Illustration of the values given in Table 2

During the test flight under consideration the altitude had been fairly constant. For the working points in Table 2 the mean altitude is about 1545m (see third diagram in Figure 8). The ground test had been performed at a location with an altitude of 350m as stated in Table 2. As can be taken from the second diagram the current-dependent temperature profiles of flight and ground test are the same, despite a negligible difference of about 1K. The upper diagram in Figure 8 illustrates the differences between recirculation / dead-end operation and ground / flight testing, respectively:

- During ground test (350m altitude) the operating voltage of the dead-end module is by about 3..4V lower than of the recirculation module. This corresponds to a relative voltage decrease of about 4..6% relative to recirculation voltage.
- Likewise during flight test (1545m average altitude) the operating voltage of the dead-end module is by about 3..4V lower than of the recirculation module. This corresponds to a relative voltage decrease of about 4.4..5.5% relative to recirculation voltage.

Hence the difference between the performance of recirculation and dead-end mode seems not to change with altitude. But during flight the voltage of recirculation module (or dead-end module respectively) are several volts lower than of the same modules during ground test. Since the working points of ground and flight test do not coincide in the measurements under consideration it is not yet possible to quantify this effect exactly. Future measurements at the same working points have to be conducted during flight and on the ground to obtain comparable results.

4. CONCLUSION AND PROSPECT

In this paper data acquired during the long range flight tests in September 2012 has been analyzed with respect to the flight altitude. In section 3.1 the influence of the flight altitude on the fuel cell *system* performance during level flight has been examined. Under the given circumstances an increase in altitude of about 1200m caused a *system* voltage drop of about 9V (which is about 4% of overall *system* voltage).
In section 3.2 the differences in performance of *single modules* working in recirculation or dead-end mode have been analyzed. Operation in dead-end mode provides a by 4..6% lower voltage than recirculation operation. The altitude only has a marginal influence on this voltage drop. Voltage decrease of dead-end operation compared to recirculation operation accounts for nearly the same magnitude at an altitude of 1545m, which has been about 1200m higher than the ground test. However altitude influences performance of both recirculation operated as well as dead-end operated modules in the same order of magnitude.

The presented results deliver clear indications for more detailed research. In future steps air pressure and ambient temperature will be monitored along with the flight data. Flight tests will be performed at different defined fuel cell power levels at constant pressure altitudes to be able to quantify the influence of altitude on fuel cell performance more exactly. In addition ground tests will be performed with the same load profiles and the same working points to assure a better comparability between ground and flight tests.

[1] Renouard-Vallet, Gwenaelle and Saballus, Martin and Schumann, Peter and Kallo, Josef and Friedrich, K. Andreas and Müller-Steinhagen, Hans, Chemical Engineering Research & Design, 90, 3-10, DOI: 10.1016/j.cherd.2011.07016, ISSN 0263-8762 (2012).

[2] Barbir, Frano; PEM Fuel Cells – Theory and Practice; Elsevier Academic Press, ISBN 978-0-12-078142-3, 2005