A COMPARISON OF SOLID OXIDE FUEL CELL DESIGNS AS ENERGY SOURCE FOR THE ALL-ELECTRIC AIRCRAFT

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Keywords: *fuel cell; aircraft systems; fuel consumption*

Abstract

The development of new aircraft system architectures for the so-called all-electric aircraft results in a highly increased electrical power demand from the systems. This electrical power can be provided by generators which convert engine shaft power into electrical power, and auxiliary power units on ground with engines off. Fuel cell systems may be an engine-independent alternative to this combination. Different system designs and alternative integration modes are presented in this paper and linked to their impact on aircraft performance. While the assessment of fuel cells on system level has been the object of many studies, the focus of this paper is the performance evaluation on aircraft level.

1 Introduction

Aircraft consume electric power for the supply of their systems such as lighting, galleys or electro-hydraulic actuators. In conventional aircraft, this electric power is provided by generators which are driven by the engine shaft. On ground, with engines off, aircraft use auxiliary power units to provide power to the aircraft systems.

Fuel cells can be an alternative to the combination of engine generators and auxiliary power units. As the fuel cell is independent of the engine, it may provide electric power in flight as well as on ground. Side effects of this technology may be water production and reductions of noise, emissions and fuel consumption.

2 The All-Electric Aircraft

Recent system technology developments tend to electrically supplied aircraft systems instead of hydraulically and pneumatically supplied ones. The development and assessment of such system technologies is the object of investigation in many research programs such as *Power Optimised Aircraft* [6] (POA). First steps toward the all-electric aircraft, which would abandon completely hydraulically and pneumatically supplied systems, have been done by BOEING with the B787 [5] and by AIRBUS with the A380 and the currently developed A350. The all-electric aircraft uses various new system technologies:

- **New generator technologies** like switched reluctance or permanent magnet machines reach higher efficiencies than today's integrated drive generators (IDG), which equals a reduction of system power demand in the same order of magnitude as less shaft power has to be taken from the engine spools. The generators of the POA program are described in [11].

- **New actuator technologies** such as electro-hydrostatic actuators (EHA) or electro-mechanical actuators (EMA) consume less power in most operating conditions than today's electro-hydraulic servoactuators (EHS). Although the power consumption of the primary flight control system is comparatively low, the benefit comes with the mass reduction due to the replacement of the hydraulic piping system. The lack of a hydraulic power system leads to the necessity to supply all today's hydraulically supplied systems like the landing gear system with electric power as well.

- **New wing ice protection systems** based on electro-impulse (EIDIS) or other technologies promise considerable reductions in power demand. However, as icing conditions happen to occur in certain flight conditions only, anti- and de-icing systems are usually operated in climb and descent phases only. Their influence on fuel consumption is thus dominated by their mass, especially on long-range missions. Additionally, the use of electrically supplied ice protection systems leads –in combination with bleedless environmental control systems– to a possible elimination of the bleed air piping.
- **Electrically supplied engine systems** do not longer depend on the engine spool speed as conventional engine systems, which are supplied mechanically by the engine gear box. Besides, the loss of the engine gear box means a reduction of friction losses.
- **Bleedless air conditioning systems** use electrically driven compressors, which pressurize the air mass flow to the required level. Conventional systems use bleed air, which is taken from the engine's compressor section. As the pressure at a certain compressor stage depends on the operating condition of the engine, pressure level and temperature of the air mass flow taken from the engine are higher than required in most flight conditions. According to [5], conventional environmental control systems waste about 30% of their energy by pre-cooling the extracted bleed air before usage. Data for the bleedless air conditioning system is taken from [3].

The substitution of conventional systems with electrically supplied ones comes along with a highly increased electrical power demand, which today is provided by generators driven by one of the engine shafts. Generators of each type take shaft power from one of the engine's compressor spools and convert it into electrical power, which results in an increased fuel consumption of the engine.

As the aircraft engines are not running all the time on ground, aircraft need auxiliary power systems to supply the systems continuously. With the engines off, today's aircraft use auxiliary power units (APUs) which are not used during flight, but increase fuel consumption due to their mass. This combination of generators and APUs may be replaced with a fuel cell system, which is able to provide electrical power on ground and during flight.

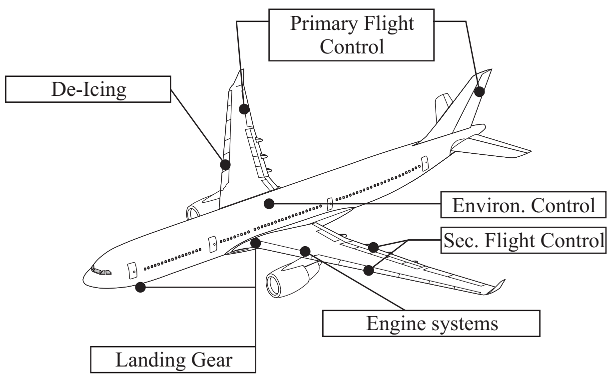

Fig. 1 Newly electrified systems in the All-Electric Aircraft.

The concepts for the replacement of conventional electric power generation systems with fuel cell systems may be divided into two categories:

- **Replacement of auxiliary and emergency systems** such as APU and RAT. In this case, the fuel cell will probably not be able to achieve its full potential, as –same as for the APU– the mass has to be transported the whole flight while its benefits are on ground only.

- **Replacement of the complete electrical power generation system** including APU, RAT and generators. This is the most challenging option. As the fuel cell system (or better the combination of redundant fuel cell systems) is the only primary energy source (with still remaining batteries), very high requirements are made to the reliability of the fuel cell system, especially if the ram air turbine is replaced as well. This option would also enable the concept of an engine without any power offtake which could be optimized for pure thrust production.

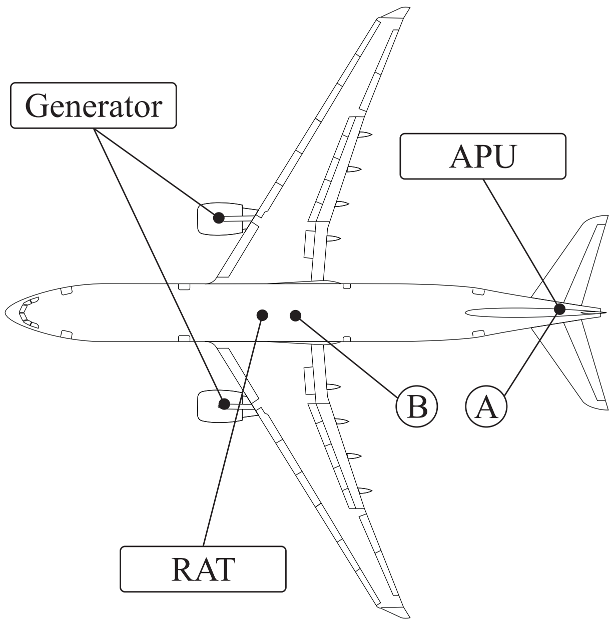

Fig. 2 Location of conventional electrical power generation system components and possible fuel cell locations (A), (B).

For an application on an all-electric aircraft with 250 passengers, the power generation system will have to provide a nominal electrical power of approximately 700kW to 900kW, depending on the type of aircraft and the technology of the specific systems. The fuel cell architectures in this paper have been designed for a nominal power of 700kW and are compared with a generator architecture sized for the same nominal power.

3 Fuel Cell System

Fuel Cells convert chemical energy contained in the fuel directly into electrical energy without the loop way of conversion into thermal and mechanical energy in conventional carnot processes.

There are different fuel cell types working on different temperature levels, made of different electrolyte and electrode materials and with variable function modes. The two most popular types are the low temperature polymer electrolyte membrane (PEM) fuel cell and the high temperature solid oxide fuel cell (SOFC). The PEM consists of a polymer membrane conducting hydrogen ions at approximately 80^{o}C. It works only with hydrogen as fuel, carbon monoxide is toxic for the materials. The SOFC in contrary consists of a oxide ions conducting ceramic membrane which works at approximately 800^{o}C. The design of a SOFC is presented in figure 3. SOFC can be run with nearly all organic fuels after preprocessing because of the oxygen conducting way of working. This is an advantage regarding single fuel use on aircraft level.

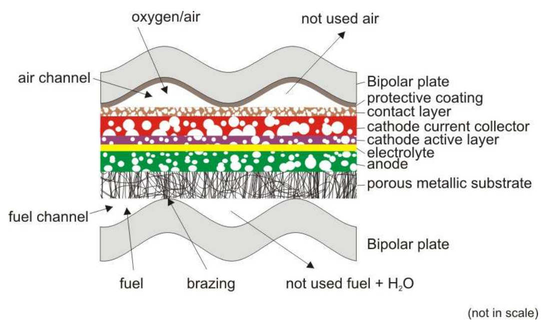

Fig. 3 Fuel cell system power output

Like batteries fuel cells produce a certain cell voltage and a size determining power density. To reach a higher output voltage fuel cells are put together to so called stacks.

The fuel preconditioning in an aircraft with Jet fuel on board is obviously kerosene reforming. It consists of the cracking of longer hydrocarbons into hydrogen and carbon monoxide as fuel and water, carbon dioxide and others as inert gases. This can be reached by different chemical reactions. There is first the exothermic, partial oxidation with a small amount of oxygen and second the endothermic, steam reforming called reaction of hydrocarbons with water [8]. The combination of both processes is called autothermic reforming, where hydrocarbons, water and a small amount of oxygen are mixed [10].

For PEM application further fuel conditioning is required to remove the toxic carbon monoxide. This includes high temperature and low temperature POX (partial oxidation) and shift reactors [8]. An alternative can be the use of pure hydrogen as fuel for small scale systems or in a hydrogen aircraft.

As the power density of fuel cells is increasing with increasing operation pressure, the use of a compressor is feasible. A gas turbine is regarded as a possible solution for the combination of gas compressor, expander and generator. Depending of the compression rate the system works on different pressure levels. Assuming a constant compression rate the system pressure varies with the input air pressure.

As not all fuel can be used in the fuel cell an afterburner is implemented where the anode and cathode off gases of the fuel cell are mixed and completely burned. The additional gained heat is used in the system to heat up the feed flows and transformed to electric energy in the turbine attached generator.

The thermal energy exchange system consists of several heat exchangers heating up the reformer and fuel cell feeds while cooling the offgas of the afterburner. Further into the fuel cell stacks integrated heat exchangers are keeping the fuel cell temperature on a constant level.

A water condensing system is also part of the thermal system. The offgas contains a certain amount of water needed for reforming and in the aircraft. It is cooled by air, which is heated up in this way and can be further used by the aircraft.

Furthermore several pumps and a water storage are part of the system.

3.1 Fuel Cell System Linking to Aircraft

The interfaces between fuel cell systems and aircraft are similar to other power generators the electric power supply, but also water and heat in terms of hot air. The fuel cell system consumes fuel and air from the aircraft. This can be realised in different ways.

The fuel supply is standing to reason Jet fuel to be preprocessed in the fuel cell system as mentioned above. Another possibility will be the supply with pure hydrogen appropriate for small scale systems. If the all-electric aircraft will be driven by alternative fuels, the system fuel preprocessing has to be adopted.

The air supply can be arranged in different attempts. The first approach is as stand-alone case with RAM air supply for reforming, fuel cell air feed and cooling. The second design is supplied with cabin exhaust air. A third way is to feed hot cabin exhaust air from behind the ECS heat exchangers at about 400 K.

Table 1 Fuel cell system parameters.

	temperature / K	pressure / bar
kerosene water	298 298	1.38 2.1
ram air	216	0.27
cabin exhaust air	295	0.75
high temperature air	400	0.75
ground air	298	1.013

For RAT replacement a small compact fuel cell system seems to be adequate. As the system requirements are fast emergency startup, short runtime and ideally high power density a low temperature PEM fuel cell system supplied with compressed hydrogen and oxygen could be a solution.

The replacement of the APU in its original application could be realised in different ways. For non continuous use a similar solution as proposed for RAT replacement could be feasible. For continuously running APU also more complex systems as PEM or SOFC with fuel preprocessing are viable.

Main power supply replacement for all electric aircraft could be also a possible application for fuel cell systems. Therefore, PEM or SOFC systems including fuel reforming and heat management are possible. For this application one kind of SOFC system design is regarded in detail as described below.

3.2 System Model

The fuel cell system under consideration consists of a solid oxide fuel cell stack combined with an auto-thermal Jet A fuel reformer, two integrated heat exchangers, an afterburner, a gas turbine with generator and a condenser for recovery of excess water. Part of the condensed water is reused for reforming; the remainder is used in the aircraft.

The fuel cell system simulations have been carried out using the process simulation software CHEMCAD. The fuel cell stack model is based on laboratory measurements of a metallic substrate supported vacuum plasma sprayed cell developed by DLR with pure hydrogen as fuel and air as oxidant [7]. The pressure dependence is estimated according to [12]:

$$\Delta V = 0.059 * \log p_2/p_1 \qquad (1)$$

The implemented characteristics are shown in figure 4. The number of cells is designed for the demanded power output at 0.8 V cell voltage.

The parameters used for the simulation of the fuel cell system are:

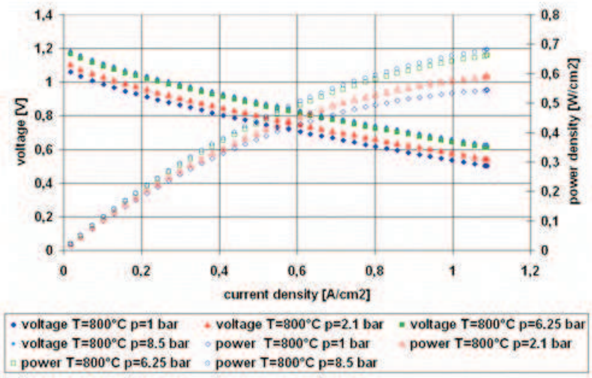

Fig. 4 Fuel cell characteristics for different pressure levels

Table 2 System component parameters.

fuel cell temperature fuel cell pressure air to fuel ratio hydrogen utilization carbon monoxide utilization	1073 K 2.1 to 8.45 bar $\lambda = 2$ 80 % 50 %
reformer temperature air to fuel ratio steam to carbon ratio	app. 1073 K $\lambda = 0.3$ 1.5
compressor efficiency	85 %
turbine efficiency	90 %
heat exchangers	ideal
separator	ideal
burner	complete combustion
component heat loss	10 %
component pressure loss	0.1 to 0.2 bar

The reforming reactor is simulated by calculating the chemical equilibrium of the partial oxidation and the steam reforming reaction. It is running in adiabatic mode. For simulation of kerosene a mixture of 79 % n-Undecane ($C_{11}H_{24}$), 10 % Propylcyclohexane (C_9H_{18}) and 11 % 1,2,4-Mesitylene (C_9H_{18}) is used. The steam to carbon ratio S/C is 1.5 and the air to fuel ratio is 0.3. The resulting reformate gas mixture is [9]:

- 28.8 vol.% hydrogen,
- 11.6 vol.% carbon monoxide,

- 7.5 vol.% carbon dioxide,
- 19.5 vol.% water,
- 32.6 vol.% nitrogen.

The following values were analyzed: mass flow of Jet A fuel, mass flow of air, mass flow of recovered water, mass flow and composition of the off-gas, compressor and turbine power and the heat load of the condenser.

3.3 System Architecture Variation

Two system architectures were designed with different integration targets. Architecture A (see figure 5) is a stand-alone design with power and water provision to the aircraft. Air is compressed, mixed with water, heated up and fed to the reformer, where kerosene is injected. The resulting reformate is fed to the anode side of the fuel cell. The other part of compressed air is heated up in heat exchanger 2 and entering the cathode side of the fuel cell. Afterward the fuel cell offgas streams are mixed and completely burned in the afterburner. The burner offgas is first used to heat up the cathode and reformer air feed flows. The same offgas stream is then used to cool the fuel cell stack in the integrated heat exchanger. It is then expanded in the turbine and partly cooled down in the condenser. The water content is separated and partly fed back to the system. The cooled amount of offgas is selected that the aircraft is delivered with 100 l/h water.

Architecture B has the same design as architecture A, but the offgas is only expanded to a level of approximately 1 bar, to use its energy content in the aircraft.

Architecture C is designed without system internal expansion. The off gas from behind the afterburner is passed directly to the aircraft for using its energy content in a thrust nozzle.

3.4 Different power levels

Three systems on different power output levels are regarded. The study is carried out for different power levels of 400 kW, 600 kW and 1000 kW fuel cell nominal power. The stacks and thus the number of fuel cells are sized for a optimum cruise performance at 0.8 V. The system power output depending on the performance of the gas turbine is slightly higher.

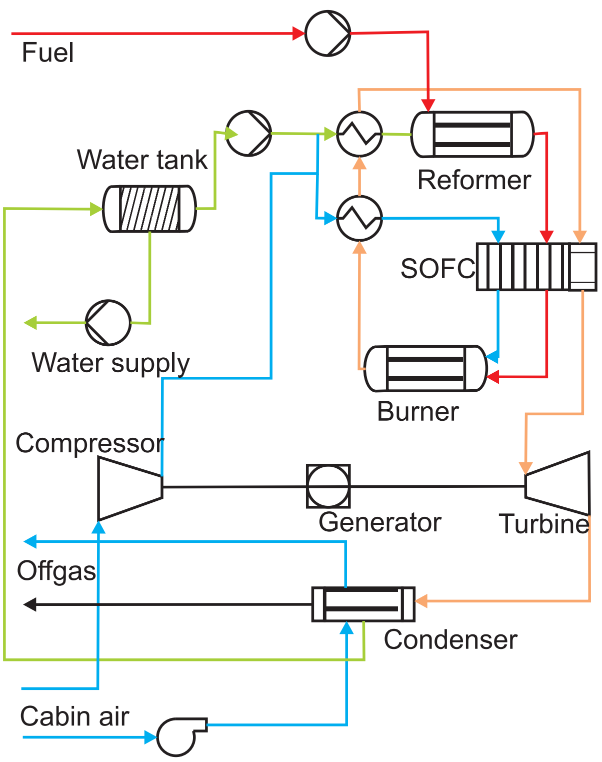

Fig. 5 Fuel cell system architecture

On ground all systems are supplied with air at standard condition. The fuel cell stack regarded for on ground operation corresponds to the aircraft supplied system with the same number of cells. The RAM air supplied system architecture works on a lower pressure level, thus the power density is smaller and the required number of fuel cells is higher resulting in a rise of system mass.

3.5 System Mass Estimation

The system design for 1000 kW is the basic data for the estimation of system mass and volume. The dimension of the evaporator, the heat exchanger and the condenser were estimated. For the detailed description of the estimation see [1].

The SOFC, the evaporator, the reformer, the heat exchanger and the afterburner are integrated in a pressure vessel. Advantages of this design are the reduction of material stress of the components and thermal losses. The condenser, the water tank, the gas turbine and the pumps are placed outside the pressure vessel.

The mass of the pressure vessel was calculated according to the standard of the German guideline of pressure vessel (DGR) with 1950 kg. This guideline and the used materials are for stationary applications and therefore a high potential for system mass reduction lies in this component.

An important influence to mass and volume of the SOFC is given by the power density. It depends on the provided fuel, operating temperature and operating pressure.

The cell design composes the base of the following calculations. The mass of one fuel cell is estimated to 160 g. One stack consists of 30 single fuel cells. The mass of a manifold was estimated to the double of a fuel cell mass. The specific power density was assumed to 500 mW/cm^2. The total mass of the stacks is 2475 kg.

The reformer is based on the cylindric coat and the inside monolith carrying the catalyst. It is constructed with a length of 635 mm and 250 mm diameter. The wall thickness was estimated to 5 mm and a catalyst porosity of 80 %. This results in a mass of 150 kg for the reformer.

As reference the gas turbine M250 - C20R from Rolls-Royce was regarded. Selected parameters were the power output of 280 kW, the air-mass flow of 1.73 kg/s and the total mass of 74.5 kg. The implemented generator mass was estimated with 0.5 kg/kW$_{el}$, a typical value for nowadays generators used in aircraft. Thus, the weight of the gas turbine and the generator with a power of 370 kW$_{el}$ is 185 kg.

The total weight of the 1000 kW fuel cell system with all components including piping and insulation is thus 6526 kg. This results in a specific system power of 5.6 kg/kW$_{el}$ for architecture A and B.

4 Fuel Cell System Simulation Results

The following results present simulations for different power levels and different integration modes. For simplicity of the presentation only architecture A in cruise condition and on ground is regarded. For better comparison of the results the fuel cell power output is fixed to a constant level. Therefore the whole system power outputs are varying.

The system performances show clear trends regarding the different integration designs. On ground with the same number of cells as with air supply from the aircraft the power output (see figure 6) is lower than on flight with aircraft air supply and higher than with ram air supply. As the system offgas is expanded to a pressure level equal to the inlet pressure the gas turbine has better operating conditions in cruise with air from the aircraft. The operating point of the fuel cell on ground has best conditions with an operating pressure of 8.5 bar and a cell voltage lower than 0.8 Volt.

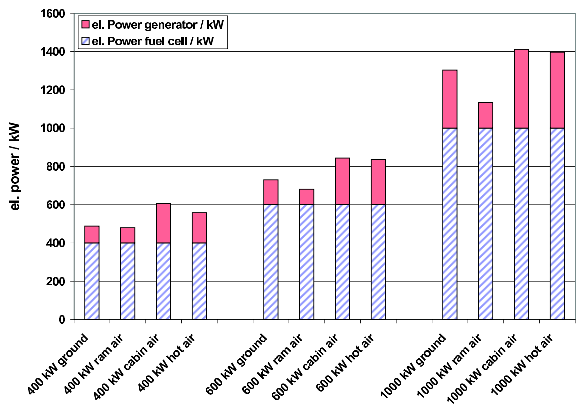

Fig. 6 Fuel cell system power output

With ram air supply in cruise the gas turbine performance is equal as on ground but the fuel cell operating pressure is at the lowest level with 2.1 bar. Also the number of cells needed to reach the demanded power output at a working point of 0.8 Volt is higher than with air from the aircraft.

The best system performance is reached with air supply from the aircraft in 39.000 ft flight altitude where the system with cabin air is slightly better than the one with hot air supply. The gas turbine has best operating conditions with an inlet pressure of 0.75 bar and an outlet pressure of 0.27 bar. The fuel cell stack operating conditions and therefore also the stack size are identical.

The kerosene feed (figure 7), the water feed (figure 9) and the SOFC and reformer air feed flows (figure 8) show similar tendencies for the integration modes. For the two aircraft air supplied designs the feed flows are identical because of identical reforming and fuel cell operating conditions.

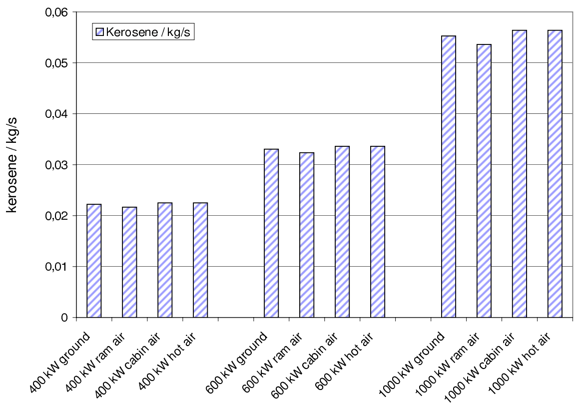

Fig. 7 Fuel cell system kerosene feed

The ram air supplied system needs less feed because of the lower fuel cell operating pressure level.

On ground the system consumption is slightly smaller than in flight condition with aircraft air supply due to slightly increased operation pressure and the shifted fuel cell operating point at a cell voltage of app. 0.83 Volt.

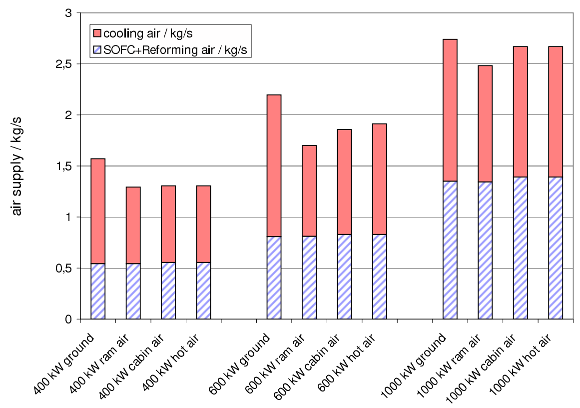

Fig. 8 Fuel cell system air feed

The cooling and condensation air consumption (figure 8) is the lowest for the ram air supplied system due to the lowest inlet temperature of -57^{o}C.

Because of the increased pressure and a cooling temperature of 25^{o}C the amount of needed cooling air is the highest in on ground operation mode.

The two system architectures with air supply from the aircraft show similar cooling air demands, the hot air supplied system needs slightly more because of the slightly higher offgas temperature.

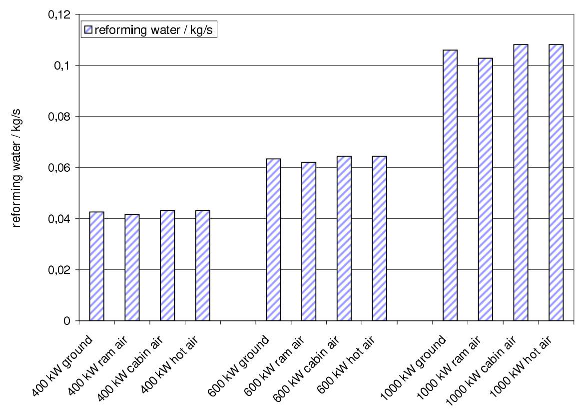

Fig. 9 Fuel cell system water feed

Regarding the electric power dependent fuel consumptions (figure 10) the systems supplied with air from the airplane show a much better performance than those with ram air supply. On ground the system performance is better than with ram air due to the shifted operation point of the fuel cell.

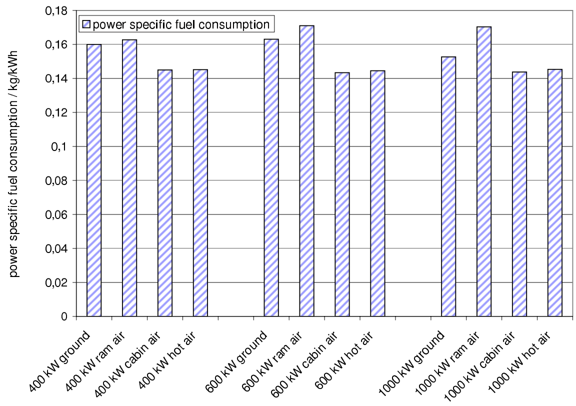

Fig. 10 power specific fuel consumption

The produced water delivered to the aircraft was fixed to 100 l/h. This amount corresponds to the middle water consumption of a long range flight.

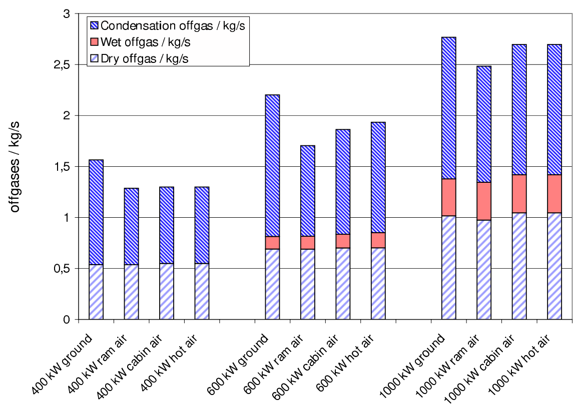

Fig. 11 Fuel cell system offgases

The system offgases (see figure 11) are split into different streams. After expansion only the amount of offgas needed to recover the system and aircraft water consumption is cooled down. The other part is mentioned in figure 11 as wet offgas. The system architectures with 400 kW power output are producing exactly the required amount of water. Therefore no wet offgas is mentioned.

The dry offgas is the cooled fraction after water separation. It corresponds to the amount of water required by the aircraft and the system itself.

The condensation offgas represents the cooling air flow heated up in the condenser. Depending on the system integration its temperatures are between 260^{o}C and 380^{o}C. This amount of hot air could be further used in the aircraft for example for wing de-icing.

5 Assessment on Aircraft Level

The analyses on aircraft level have been done using the simulation tool SYSFUEL, which is described in [3] and [4].

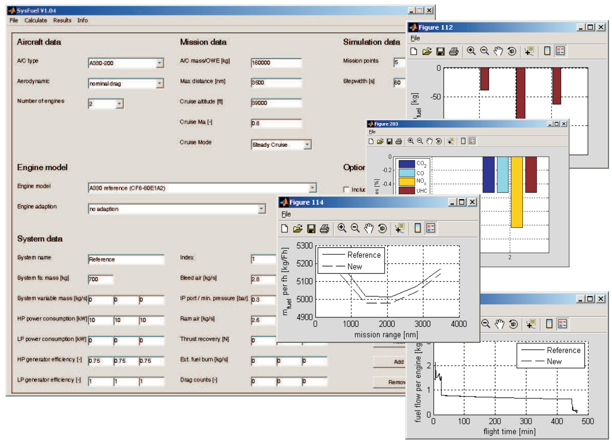

Fig. 12 SYSFUEL user interface.

Some of the results from the fuel cell assessment are shown in figure 13, which is taken from [2]. The figure shows the comparison of the impact of the three fuel cell system concepts on the mission fuel mass. As can be seen, with the assumed power density of 6.4 kg/kW for the baseline, all considered fuel cell system designs result in a higher required mission fuel mass than the conventional reference system (generators and APU). Depending on the mission range, a power density of approximately 4 kg/kW on system level (including all fuel cell system components) should be achieved to reach a break-even in terms of fuel consumption. This value assumes the consumption of cabin exhaust air for internal processing; if the fuel cell needs ram air for internal processing, this value decreases to under 2 kg/kW.

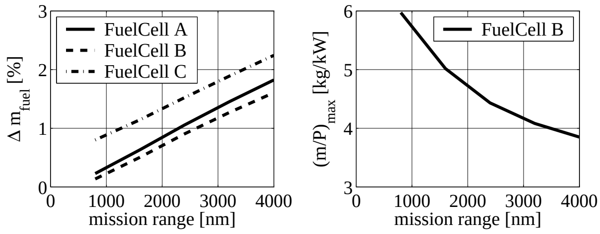

Fig. 13 Fuel consumption changes in dependence of mission range for fuel cells using cabin air with different energy recovery options. h=39000 ft, Ma=0.8

6 Conclusion

The replacement of auxiliary power units and generators with SOFC type fuel cell systems may be a promising system architecture scenario. Besides the benefits on ground (lower noise and emissions compared to conventional APUs), the application of a fuel cell system as a primary energy source to aircraft systems results in a decreased mission fuel consumption. For this, a power density of the complete fuel cell system of 4kg/kW –depending on the fuel cell system design– has to be realised. This value already considers the fuel cell's secondary benefits such as water usage during flight.

Literatur

[1] BUNDSCHUH, N.; LENZ, B.; BROMBERGER K.: Solid Oxide Fuel Cell Systems for aircraft application. *Journal of Power Sources*, 2005.

[2] DOLLMAYER, JÜRGEN; BUNDSCHUH, NICOLA; CARL UDO B.: Fuel Mass Penalty Due To Fuel Cells And Generators As Energy Source Of The All-Electric Aircraft. In: *Aerospace Science And Technology. To be published.*, 2006.

[3] DOLLMAYER, JÜRGEN; CARL, UDO B.: SysFuel - A New Methodology for Prediction and Analysis of Fuel Consumption due to Aircraft Systems, DGLR-JT2005-240. In: *DGLR-Jahrestagung - Deutscher Luft- und Raumfahrtkongress*, Friedrichshafen, 2005.

[4] DOLLMAYER, JÜRGEN; CARL, UDO B.: Consideration Of Fuel Consumption Caused By Aircraft Systems In Aircraft Design, ICAS-2006-221. In: *25th International Council of the Aeronautical Sciences (ICAS) Congress*, Hamburg, 2006.

[5] DORNHEIM, MICHAEL A.: Massive 787 Electrical System Pressurizes Cabin. In: *Aviation Week & Space Technology*, 2005.

[6] FALEIRO, LESTER: Power Optimised Aircraft - The Future of Aircraft Systems, AIAA 2003-PP10127. *AIAA/ICAS International Air an Space Symposium and Exposition: The Next 100 Years*, Dayton, Ohio, USA, 2003.

[7] LANG, M.; FRANCO, T.; SCHILLER G.; WAGNER N.: Electrochemical Characterization of Vacuum Plasma Sprayed thin Film Solid Oxide Fuel Cells for Reduced Operating Temperatures. *Journal of Applied Electrochemistry, Vol.32*, Kluwer Academic Publisher, Niederlande, 2002.

[8] LARMINIE, JAMES ; DICKS, ANDREW: *Fuel Cell Systems Explained.* John Wiley & Sons, Ltd., Chichester, England, 2000.

[9] LENZ, B.; BUNDSCHUH, N.: Performance of a Combined Reformer/SOFC System for Aircraft Application. *Sixth European Solid Oxide Fuel Cell Congress*, 2004.

[10] LENZ, B.; AICHER, T.: Catalytic Autothermal Reforming of Jet Fuel. *Journal of Power Sources*, 149, 44-52, 2005.

[11] NEWMAN, RICHARD: The More Electric Engine Concept. *World Aviation Congress, Reno, Nevada, USA*, 2004-01-3128, 2004.

[12] U.S. DEPARTMENT OF ENERGY - NATIONAL ENERGY TECHNOLOGY LABORATORY: *Fuel Cell Handbook.* DOE/NETL-2002/1179, Morgantown, West Virginia, USA, 2002.