ASPECTS OF PROCESS DESIGN OF SOFC HYBRID SYSTEMS FOR AERONAUTIC AND MARITIME APPLICATIONS

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ABSTRACT

The integration of fuel cells into transport systems accompanies the development of the mechatronic or all-electric systems replacing classical mechanical solutions. The hybrid cars entering the markets are the first visible step of this development. These systems allow a better approach of reversible solutions because the possibility of charging and discharging of electric power allows more reversible system architectures. A specific challenge is the integration of fuel cell systems and particular SOFC hybrids onboard aircraft and ships as new components. The change of the architecture will lead to All-Electric Ships and More Electric Aircrafts. Even though hydrogen might be a long-term solution, the necessary storage of fuel and the world-wide availability demand kerosene and maritime diesel as the application relevant fuels. The design of SOFC hybrids has to consider the optimal thermal integration of the fuel processing. The use of a Matlab-Simulink based model showed that the efficiency of a reference SOFC hybrid cycle may vary between about 50 to 70%. The influence of part load operation has been considered between an altitude of 0 and 12000 m to simulate real aircraft operation. The electric efficiency was between 60 and 65%. Part load calculations give valuable information about the control regime of the BoP.

INTRODUCTION

The development of transportation systems is generally leading to an increase of electric components and a reduction of the classical mechanical components. The future vision is the all-electric or mechatronic system. However there are different motivations, but some of the most important aspects are to contribute to a more sustainable development and to cut increasing energy cost by an increasing efficiency. This development concerns road, sea and air transportation as well. Electrochemical devices and in particular fuel cells and specific SOFC hybrids will become key components of these systems. The most ambitious demands on the specification of fuel cell system are defined by the aircraft industry. These specifications cover all other transportation applications as well, however the possible specific market prices of the relevant fuel cell systems, usually related per kW, clearly differ. The general lay out principles defining the integration of a fuel cell system into an all electric transportation system are independent of the application; however, the
available technology restricts the technical possibilities and is responsible for the obvious different technical solutions.

OVERALL SYSTEM INTEGRATION PRINCIPILES

Generally an increase of the system efficiency of any transportation system can be only reached if the entire (transportation) system can be made more reversible. Fig. 1 shows an approach to increase the efficiency by defining two sub-systems: a vehicle system responsible for the transportation task itself and an energy converter supplying energy demanded by still remaining irreversibility. This delivers the principles of a two step lay out strategy.

![Diagram of system integration principles](image)

Figure 1. Reversible system structure efficiency.

The efficiency of a vehicle system can be increased by approaching the reversible structure of the transportation task. Any real system - even in a reversible structure - produces irreversible losses and thus a continuous demand on energy to be supplied by an energy converter that has a principle reversible structure as well. SOFC hybrid systems are the most adequate developments available.

![Diagram of pendulum motion](image)

Figure 2. The motion of a pendulum as a pattern of the system lay out.
The well known motion of an ideal pendulum shows very clearly how a reversible transportation system works, fig. 2. The transport distance AB is defined by the points A and B as the places of the maximum height of the transported mass m of the pendulum. At these highest points all the energy of the system is stored in the potential energy \( m \cdot g \cdot h \). The height h is the difference between the highest and the lowest point of the mass m. At the lowest point in the medium between A and B all energy of the system is converted into kinetic energy \( \frac{m \cdot v^2}{2} \). However this system is principally reversible we know from experience that we have to add energy continuously to keep a real pendulum running, caused by the friction within the bearing and the air resistance. This simple example shows that we need a system architecture that allows an internal conversion and storage of the system’s energy and an external energy converter including storage to supply the necessary work.

The demands of the customer influence the development of a technical solution on the first place and the knowledge of the theoretical background discussed above has to be used to fulfil these requirement. Fig. 3 illustrates these main influences on the technical solution leading finally to the system specification. The availability of the system is a key issue in general because all business plans of the customer rely on it. A lightweight and compact design allows a high commercial utilisation of the available total weight and space. The availability and the storage a high amount of energy in a limited space and weight is the main reason to use a fuel and an energy converter -a fuel cell in future- instead of a direct storage of electricity. The increasing energy prices and the demands on a more sustainable economy lead to an increasing interest on an efficiency increase. Additionally an efficiency increase leads to a reduction of the necessary fuel to be stored per transport distance. Operational and safety conditions lead to an increased interest on the system dynamics. Automation and an increasing amount of electronic equipment lead to an increasing demand on onboard electricity.

Fig. 4 gives an overview of possible solutions for general transportation systems by using SOFC technology. The demands of reversible structures show that electricity is a very suitable form of energy to be stored and used internally and to be supplied onboard by the fuel cell system. A similar system architecture is already the design of hybrid cars entering the market today however internal combustion engines are still used there. Because the reversible structures need electric storages as batteries, these are more complementary
than competitive to fuel cells and in particular SOFC hybrids. The function of the electric storage is defined by a high flexibility of charging and discharging electric power and a lightweight and compact design with a high efficiency.

![Available technology diagram](image)

**Figure 4. Theoretical conditions and technical realisation options.**

The onboard SOFC hybrid system including the fuel storage must operate with the highest possible efficiency at the lowest possible weight and volume. However this double hybrid system design seems to be an almost realised vision of a future hydrogen economy this fuel is not applicable on large scale aircrafts or ships today or in a near future. If we consider e.g. the EU hydrogen roadmap there are expectations of only 1 – 5% of the cars fuelled by hydrogen in 2020 (1). Thus today fuel cell systems onboard aircraft must be designed for kerosene and onboard ships for maritime diesel as a fuel because air and sea transport need a global fuel supply logistic and a fuel with a high energy density. It cannot be expected that the problems connected with an efficient storage and a sustainable production of hydrogen are solved before the market entrance of fuel cell systems.

### ONBOARD POWER GENERATION IN AIRCRAFT AND SHIPS

The innovation of fuel cells onboard aircrafts and onboard ships will deliver a number of benefits for an increased sustainability of a new system architecture mainly by an increased efficiency and thus a less fuel consumption than today (2). The mission and technology of ships and aircrafts differs from the mission of an automobile and thus not the entire approach of a hybrid car can be adapted. For example a ship will not operate at different heights and there are no fast accelerations and slow down manoeuvres that could utilise an energy storage for the total system. Aircrafts operate at different altitudes but the weight of energy storage would be much too high to be technical attractive. But the reversible model helps to identify possible improvements as guidelines for significant integrations or separations of subsystems during design and operation. Today the integration of power generation within aircrafts and ships differs. In aircrafts the engines usually generate all energy needed during the flight, only on ground an auxiliary power unit supplies the energy needed. Onboard ships there are separated power generators, today usually diesel engines, available. They supply the necessary energy continuously. The main propulsion system of ships is based on diesel engines already combined with electric drives in some applications. But generally aircrafts and ships are on the way to change
sub- and auxiliary systems to electric systems. Future high efficient SOFC hybrids are thus the technology needed for these applications.

**Figure 5. The development to All Electric Ships (3).**

The development of ships with an electric driven propulsion system has a long tradition. The better flexibility of electric driven POD systems is an interesting motivation for merchant ships as well, however military applications were promoting electrical applications. Fig. 5 shows the development from already actual Integrated Power Systems onboard ships to All Electric Ship concepts (3). Integrated Power Systems already have an electric drive and a reduced number of prime movers resulting in a fuel savings and a reduced maintenance. The All Electric Ship concept increases automation and reduces manning, the elimination of separated auxiliary systems reduces maintenance and saves energy by a better integration.

**Figure 6. Actual and new aircraft architecture and its consequences.**

The aircraft application of fuel cells as a power generator is one of the most ambitious projects focused on future all/more electric architectures of large commercial aircrafts. The main expected benefit is the increase of the total efficiency by optimising design and operation of the main engines by supplying the different onboard power consumers only by high efficient fuel cells. Fig. 6 gives a comparison with the actual architecture. Today the main engines are used for propulsion and supply of the electric power, the hydraulics...
and pneumatics' systems' energy demand and the bleed air as well. The operation of any main engine is thus an optimised compromise of these different demands. The main engines are out of service in a park position on ground and the energy is supplied by the APU (auxiliary power unit). The efficiency of the power generation of the main engine is in the order of 40% and that of the APU in the order of 20%. The new aircraft architecture uses the main engines only for propulsion and their operation can be optimised therefore, thus they become more reversible. The onboard fuel cell systems become the main power sources operating continuously. Electric power is the main energy source for all systems and for producing bleed air, hydraulic and pneumatic systems will be replaced. Finally the fuel cell can be used for the generation of usable water from its reaction water. The main energy saving can be expected by the better efficiency of the main engine, the much higher efficiency of the electric power generation in the fuel cell system (60 – 75%) and depending on the mission the saving of weight by reducing the water storage.

However there are different approaches on the entire system design of maritime and aircraft applications but important issues for the development and design of onboard fuel cell systems in particular SOFC hybrids are similar. A rough comparison of the fuel cell requirements of the aircraft and the ship application is given in Table 1.

Table 1. Synergies and differences for fuel cell systems in aircraft and ship application.

| Application | Aircraft | Ship |
|-------------|----------|------|
| Electric propulsion | not yet | POD |
| Power generation | 1st application | 1st application |
| Space | lowest possible | restricted |
| Weight | lowest possible | restricted |
| Mechanical stress | dynamic | dynamic |
| Hydrocarbon use | kerosene | diesel |
| Desulphurisation | needed | needed |

However, experimental unmanned systems and studies (4) showed the general possibility of a fuel cell propulsion of small aircrafts it will be quite a long way to develop a propulsion system based on fuel cells for commercial aircrafts, if generally possible. The possibility of an electric propulsion of ships has been commercially demonstrated by POD systems and the fuel cell would be an other power source only. Today it seems that the fuel cell technology will be introduced by the onboard power generation in aircrafts and ships. However weight and space needed are important issues for a maritime power generation unit as well but the real challenge of fuel cell system design is the aircraft application with its hard demands on volume and weight with 1 kW/kg and 1 kW/l for the entire system. A successful development of such an onboard fuel cell system will have a high impact on maritime and automotive applications as well by initiating comparable solutions. The control of the mechanical stresses within the SOFC stack caused by dynamic movements is another issue of high importance. New material developments for SOFC are reported here, to improve the mechanical stability of SOFC (5). However kerosene is
used as a fuel for commercial aircrafts and marine diesel for ships but the challenges of fuel processing are similar. Last but not least the desulphurisation of the fuel is an other key issue of research in all applications. However there are differences in the application and integration of SOFC hybrids onboard aircraft and onboard ships the principal design calculations and process modelling of the SOFC hybrids are similar.

SOFC HYBRID SIMULATION

The process design of SOFC hybrid systems depends strongly on the expected operational parameters and the fuel used. Being independent from the specific system to be analysed and designed, the tools for process simulation must include:

- capabilities for an easy description of flow sheets,
- calculation of thermodynamic data and chemical reactions, and
- capability of part-load calculation.

The simulation model developed at Hamburg University of Applied Sciences is based on MATLAB Simulink. The results of (6) had been used to improve the fuel cell model and the description of the chemical reactions. This general modelling tool was used to analyse different flow sheets of fuel cell systems. The description of the system behaviour during a certain mission is necessary to compare different design proposals with relevant specifications. It delivers important inputs to the design and calculation of certain components. Different types of the description of the components can be integrated into the modelling tool depending on the specific task. Fig. 7 gives an example of the component descriptions used for the here presented example.

Figure 7. Key elements for the part load simulation of SOFC hybrids.

The SOFC behaviour under part load operation is described by a mathematical model of the physical processes as presented in (6). The results of these calculations had been evaluated by experimental results from different sources. The part load description of the
heat exchangers (HEX) is based on the common e - NTU method assuming mainly convectional heat transfer. The description of the gas turbine as a unit is not an adequate method for such a system because the behaviour of a SOFC module differs clearly from that of a combustor of a gas turbine. Thus it is necessary to use a separate description of the compressor and a separate description of the turbine part of the gas turbine. Again a mathematical modelling of the physical processes might be an option but for this specific case experimental results had been used. Thus the behaviour of compressor and turbine has been integrated by polynomials describing the specific graphs.

A remarkable difference between a SOFC hybrid onboard aircraft and onboard ship is the change of the ambient state during the mission. Fig. 8 shows the dependence of the ambient pressure and the ambient temperature on the flight altitude as calculated by the ISA Standard Atmosphere model (7). A flight altitude of 12000 m will lead to a decrease of the ambient pressure to about 0.2 bar and a temperature reduction compared to ground conditions of more than 70 K. These changes of the ambient state around the aircraft have consequences on the part load operation of the turbo-machinery and the SOFC itself and have to be considered in the system lay-out.

Figure 8. Influence of altitude on the ambient state of an SOFC hybrid in an aircraft application.

The evaluation of the effects of the part load conditions and the choice of fuel processing on the performance of SOFC hybrids had been evaluated by a generalised SOFC hybrid model as shown in fig. 9. The core of the system is an SOFC module with an integrated fuel processing combining partial oxidation (POX) and reforming. Depending on the chosen excess air of the POX this fuel processor model can describe the POX operation and thermal integrated reforming process supplied with SOFC waste heat as well and all possible combinations in between. The control parameter is the excess air of the POX only. The compressed air after the compressor and the preheated fuel enter the SOFC and fuel processing module. Cathode and anode gas are burnt in a combustor before the turbine. The expanded flue gas leaving the turbine outlet is cooled by a steam generator for the process water of the reformer and a possible flue gas condenser for water generation if applicable for the mission. Target of the evaluation was to identify the influence of fuel processing on the electric efficiency of the system and the influence of part load at differ-
ent altitudes on the electric efficiency. C_{11}H_{22} was used as a model fuel. The S/C ratio was fixed at 2 and the fuel utilisation was fixed at 85%.

Figure 9. Principle SOFC hybrid concept for evaluation.

The influence of the excess air of the POX on the electric efficiency is shown as a function of the system pressure in fig. 10. The influence of the system pressure and thus the influence of the altitude is comparable small compared with the influence of the excess air of the POX. Thus these results are valid for maritime applications as well. A fuel processing by POX only delivers the lowest efficiency of about 50% while a full integrated reforming delivers an efficiency of almost 70%. This result is not unexpected because the combustion process of the POX produces an extra amount of entropy and the excess air for cell cooling has to be increased with the consequence that the waste gas loss and the parasitic losses increase as well (8).

Figure 10. Electric efficiency of the SOFC hybrid depending on system pressure and excess air of POX.
The results of the calculation of the electric efficiency depending on part load and altitude are shown in fig. 11. The dependence of the efficiency of the part load and altitude is comparable small and the best efficiency can be reached at the highest altitude in that case. The calculation shows the influence of the actual operation regime of the turbo machinery and the necessary measures for the control strategy as well. The maximum electric efficiency reached is about 65% and the minimum is about 60%. The efficiency characteristic over the load is comparably flat. Again the results of the calculation at an altitude of 0 m can be transferred to maritime application as well.

![Figure 11. Electric efficiency of the SOFC hybrid in an aircraft application depending on part load and altitude.](image)

**CONCLUSIONS**

The concept of an all electric transport system approaches the reversible transport system in general. SOFC hybrids will become a key technology for such systems. Batteries will become an interesting complementary technology. But high demands on engineering regarding lightweight and compact design have to be fulfilled specifically for the aircraft applications. However fuel cell operated propulsion could become an interesting technology on a long term for ships, but the onboard power generation at highest possible efficiency with SOFC hybrids operated with diesel or kerosene will be the entrance market. The thermal integrated reforming or the direct use of liquid hydrocarbons in the anodes is a key development to reach the high efficiency as expected and to avoid a high entropy production by POX. The control of the turbo machinery has to be specially designed for these specific applications.
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