

A Methodology for Rapid Evaluation and Sizing of Fuel Cell System Architectures for Commercial Aircraft

2011-01-2646

Published
10/18/2011

Hauke Peer Lüdders, Jan Grymlas, Enno Vredenburg and Frank Thielecke
Hamburg University of Technology

Copyright © 2011 SAE International

doi:[10.4271/2011-01-2646](https://doi.org/10.4271/2011-01-2646)

ABSTRACT

This paper presents a methodology to develop, optimize and evaluate fuel cell system architectures. The main focus is placed on the sizing and optimization process which uses the simulation tool Matlab/Simscape. A model library is introduced which contains parametric behavior models. The benefit of this is that the size of the components is not fixed by the parameters. The size of the components is driven by the energy and mass flows of each component. Thus the implicit sizing and optimization process is easy to handle and numerically robust. Illustrative results are shown for a fuel cell system.

INTRODUCTION

The reduction of the environmental impact of future aircrafts becomes more and more the main technology driver for new aircraft designs. The ACARE 2020 objectives demand a NO_x reduction of 80%, a fuel consumption and noise emission reduction of 50% for future aircrafts. In order to fulfill these requirements, a worldwide search for new technologies has started. The integration of fuel cell systems in future aircraft system architectures is a promising approach [4]. A fuel cell produces electrical power in a very efficient way without noise and pollutant emissions. However, the weight penalties of a fuel cell system require a multifunctional approach of the integration. This means that all the advantages of a fuel cell system have to be used in an optimal manner. The fuel cell system would then deliver not only electrical power, but the exhaust gases of the fuel cell (which are water and oxygen reduced air) could also be used for fuel tank inerting, fire suppression and for the water system.

During the design and evaluation of such a multifunctional fuel cell system in preliminary design phases a methodology and a tool chain with a sizing and optimization process was developed. This paper first shows the motivation for the development of this new methodology. In chapter 3 this methodology is introduced. Chapter 4 gives more details about the sizing and optimization process based on behavior parameters instead of geometry parameters for the components. In chapter 5 an example for the sizing and optimization process is presented in order to illustrate the advantages of this technique. This paper ends with a conclusion and an outlook.

MOTIVATION FOR A NEW METHODOLOGY

In the current industry practice the specific design and the sizing of the overall fuel cell system with all its subsystems and neighboring systems are developed by hand. Each component is analyzed and sized by itself. The dependencies between the components are recognized in several iteration loops. Since the components are analyzed by different engineers, these iteration loops are crucial due to hidden couplings. A system architecture is then defined and a simulation is built for this architecture using models with geometric constraints to validate the architecture. A fine tuning of the architecture can only be achieved in a limited way since any greater change of parameters may lead to undesired system behavior. This practice is very time consuming and does not guarantee optimal solutions.

Similarly to the Environmental Control System architecture [5], the challenge in defining and sizing a fuel cell architecture is that the sizing process of the components is not

explicit. This means that a set of functional requirements does not directly lead to a unique architecture with all components having a well defined size.

Figure 1 gives an example for a fan that blows air to a heat exchanger which is needed for fuel cell cooling. This fan can have a relatively small size (and hence a lower weight). However, the price for the lower size leads to an increase in the power demand for the same amount of blown air. This increased power demand leads to a larger fuel cell stack size as more power has to be provided. Thus the heat exchanger size would increase since more heat has to be released. This again would require a bigger fan. It becomes obvious that finding an optimal sized system architecture is difficult, as even the optimal size of this three component example is hard to determine. Usually, the number of components is much higher. This type of architecture sizing is called “Implicit sizing” [5]. In contrast to this, many systems like the electric power distribution can be sized explicitly. Using inverse models and a bottom-up approach, the size of the network can be determined starting from the consumers and ending at the generators [7].

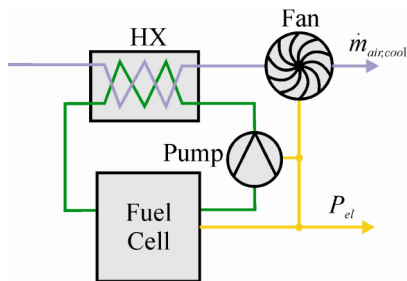


Figure 1. Simple example for an implicit sizing problem

For Environmental Control Systems explicit sizing rules are at least available for a set of conventional and well known system architectures [5]. However, the sparse experience in the integration of a fuel cell system in an aircraft system architecture makes it complicated to find a good starting point. Moreover, it has to be recognized that fuel cell technology itself is part of current research. Hence, new technology developments like High Temperature Fuel Cells can change the whole system architecture significantly [11]. For these reasons a methodology is needed which enables the system engineers to rapidly evaluate and size different fuel cell system architectures in order to integrate this complex technology in commercial aircraft with the most positive impact.

INTRODUCTION TO THE METHODOLOGY

The methodology which is introduced in this chapter (Figure 2) is based on [16]. However, in practice it was shown that especially the sizing of the system architecture has to be

improved to get a faster analysis of optimized architectures. In the second part of this chapter the used tool chain is explained.

5-STEP METHODOLOGY

Having accomplished the preliminary design phase of an aircraft [7], the methodology is employed. Hence, in the *first step* the requirements at aircraft level are known in at least a preliminary version. These requirements describe the functions of the fuel cell system at aircraft level. These functions can generally be divided in two tasks. The first task comprises the functions for the normal operation and the second task the functions for the emergency case. Moreover, there are requirements due to the environmental conditions under which the system has to operate. This contains information about the flight envelope like ambient temperature, pressure and relative humidity information ranges. The safety and reliability requirements are also very important aspects since they determine which redundancies have to be considered in order to fulfill the requirements during normal and emergency operation.

In the *second step* of the methodology the design cases for the fuel cell system have to be identified. Based on the requirements at aircraft level the points of maximum performance have to be found. This can basically be done by using the maximum power requirements at the worst case of environmental conditions by given reliability and safety requirements. As all requirements change with the actual flight phase of the aircraft, a certain number of design cases can be the result; In practice around three to four: e.g. Ground, Take off, Top of Descent.

Another important task of this *step* is to determine the system functions of the fuel cell system in order to fulfil the requirements at aircraft level and to guarantee a regular operation of the system. The identification of these functions requires system knowledge. However, it is very useful to think in functions and not in components at this stage in order to get a maximum solution space for innovative configurations. The first two *steps* require a systematic and disciplinary approach. This is crucial for receiving traceability of the solution which is indispensable especially if many people are working on the same project.

During *step 3* the architecture of the fuel cell system will be defined. The system functions from *step 2* are linked to the components that are needed by the system. Moreover, the safety and reliability requirements have to be recognized as well.

The selected architecture is the basis for sizing the components and hence for the overall fuel cell system. For this *fourth step* a comprehensive model library was created. The library contains all necessary components of the system.

For each component one model exists that owns the special property of being self-sizing. These models do therefore not have any geometric parameters. The sole used parameters are behavior parameters like efficiency factors. Moreover, each component is linked to a script which can be used to calculate the geometry and the mass by given energy and mass flows of the component. These models can be used in combination with these scripts to size and optimize the architecture for the given design cases from *step 2*. Accordingly, this *step* is the central part of the methodology. More details about this *step* are given in the next chapter.

The sized and optimized architecture of the *fourth step* will be validated in the *fifth step*. The calculated geometries of each component are used for geometric models which are available in a second model library. The fuel cell system will be simulated for whole flight mission and it will be checked if the system works in all flight phases. Moreover, a fine tuning can be done in order to reduce possible conservatism assumptions of *step 3*. After the validation the exact Key Performance Indicators (KPIs) can be determined (Additional drag of the system at each flight phase, the exact H₂ consumption during the reference flight mission). This information can now be used to verify the requirements at aircraft level of *step 1*.

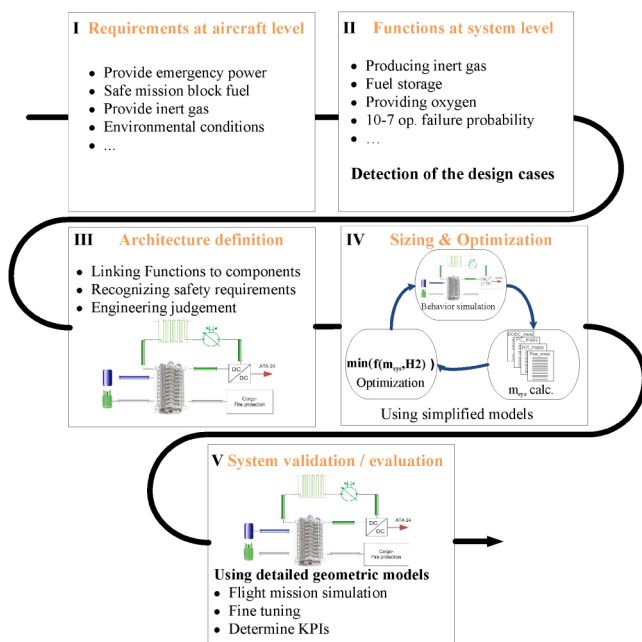


Figure 2. Methodology for developing fuel cell system architectures

CORRESPONDING TOOL CHAIN

The described methodology (Figure 2) requires a tool chain with good interfaces in order to reduce the manual transformation of data to a minimum.

In aircraft industry DOORS is an often used tool for requirement engineering. DOORS is a table-based program which enables a structured and hierarchic data management for requirements. Each requirement receives a unique number which assures the traceability in all stages of the development project [12]. DOORS can be used for the *steps 1 and 2* of the proposed methodology.

For the architecture definition a graphical user interface is recommended. In order to keep the effort at a minimum and the tool chain as short as possible Matlab/Simscape is used. The model library needed for *step 4* can be utilized for this task. Since Simscape uses an acausal modeling language, the connectors of each model can be identical with the interfaces of the real component [10]. The Simulink/Simscape framework offers a gateway which enables the user to link the aircraft and system requirements to the architecture. Tools like SyRelAn [14] can be used to accomplish the safety and reliability analysis.

The strength of the Mathworks environment becomes obvious in the *fourth step*. The used sizing and optimizing process which is described in chapter 4 uses a combination of Matlab, Simulink and Simscape. The global data tree of Simscape can directly be used within Matlab. Hence, all states and variables of the simulation can be used in Matlab without import filters [10]. Moreover, strong implicit differential algebraic solvers are available [17] to calculate the system architecture in the design cases. The optimization toolbox offers several optimization algorithms suitable for optimization studies.

The system validation and verification is also realized in Matlab/Simscape. Since Simscape uses an object oriented modeling approach it is possible that the geometric models which are needed in this *step* come from the same model class as the models of *step 4*. Hence, the corresponding component model of the *step 4* library has the same interfaces as the model of the *step 5* library. Thus, it is possible to automatically switch the system model of *step 4* to a system model of *step 5*.

SYSTEM SIZING & OPTIMIZATION (STEP 4)

This chapter describes the procedure of sizing and optimizing the qualitative specified architecture of *step 3*. For this, a special model library was developed which will be presented first. After this the use of the combination of Simulink/Simscape with Matlab for sizing and optimizing the

architecture is shown. The strategy presented in this chapter enables an effective and fast sizing process even for implicit systems.

MODEL LIBRARY

The models of this library can be characterized as behavior models. They have a minimum complexity and are parametrizable with behavior parameters. A typical parameter is an efficiency factor as this parameter does not reveal anything about the size of the component but only about the performance. One huge advantage of this kind of parameterization is that the models do not bear geometric constraints. Also the parameterization is intuitive as the decision about the desired efficiency of a fan can be easily reached without knowing the required mass flow of air and hence the size of the fan.

Another advantage of these kind of models is that a consistent solution of the architecture can be assured since the size of the components is flexible and hence the energy and mass flows of each component are not bounded during the sizing process.

In order to reduce the complexity to a minimum, the models usually only describe the static behavior.

This type of model library is well suited for optimization studies because each component incorporates only one behavior parameter and optionally one fixed parameter which is given by requirements. Another benefit of using the so called behavior parameters is that during an optimization study not all parameters of all components have to be recognized. This is due to the fact, that the size of the components is not fixed by a behavior description. Hence, a component can vary its size although its parameters are not direct part of the optimization set. This is crucial when analyzing and optimizing complex and implicit systems since inconsistencies can be prevented. An example would be a system with too small cooling pipes for a required cooling flow. This can speed up the optimization and makes it more robust against numerical problems.

In the following, three models are presented. In this context the technical difficulties of this kind of modeling are discussed further.

Cooling Pipe

Pipes are important components since they encompass a significant fraction of the total system weight. The pressure loss in the pipes increases with the velocity by square. Hence, a certain diameter is needed for a given mass flow in order to get the pressure loss and the noise into reasonable ranges. The pipe model presented in [Figure 3](#) is modeled without geometric constraints.



Figure 3. Cooling pipe model

In [Table 1](#) the needed parameters of this model are listed. In [Tables 1,2,3,4](#) all parameters are labeled with an “opt” if they are suitable as an optimization parameter, they are labeled with “giv.” if they are defined by requirements.

Table 1. Parameters of the pipe model

Name	Unit	Opti./Requi.
L_{pipe}	m	giv.
Δp_{spez}	Pa/m	opt.

The first parameter L_{pipe} describes the length of the pipe. This parameter is set by the requirements since the location and installation space cannot be analyzed in detail when using this methodology. However, it is possible to compare several space requirements with each other. The second parameter Δp_{spez} describes the behavior of the pipe. It simply states how much pressure drop will occur per meter pipe length for the actual simulated design case.

Hence, the following equations give a full description of the energy and mass flows of this component. Since only the static behavior is modeled, the mass flow equation is:

$$\dot{m}_{Fluid,1} = \dot{m}_{Fluid,2} \quad (1)$$

The pressure drop is modeled with the given parameters:

$$\Delta p = p_1 - p_2 = \Delta p_{spez} \cdot L_{Pipe} \quad (2)$$

The temperature increase due to friction is neglected ($T_1 = T_2$). This assumption is reasonable since the heat transfer due to convection to the environment is also neglected. It can be hypothesized that the heat transfer is larger and hence the assumption is conservative.

It becomes obvious that this pipe model does not have a specific size. Only the desired behavior (in this case the pressure drop) is modeled. This behavior description is valid for every size. The required diameter can be calculated in a processing step with the desired pressure drop and the mass flow which runs through the pipe. For more details see [chapter 4.3](#).