BRIDGING THE GAP: DESIGN OF A SOFC APU STACK FROM AN AUTOMOTIVE SUPPLIER'S PERSPECTIVE

Michael Stelter
Webasto AG
Speicherstraße 3, D-17033 Neubrandenburg, Germany

ABSTRACT

Automotive industry procedures were employed to design a SOFC APU stack that meets high performance targets while at the same time is optimised for cost effective manufacturing. The stack requirements were derived in a structured top-down approach from commercial and technical restraints. Tools and procedures involved are described in principle. A bipolar plate serves as an example on how the differing aspects were combined in a concrete design.

INTRODUCTION

Webasto AG of Stockdorf, Germany, a supplier of roof and comfort systems to the automotive industry, is developing a SOFC based auxiliary power unit (APU) for mobile and stationary use. Integral part of the development work is the SOFC stack. Webasto is designing and manufacturing the APU stack module in a partnership with H. C. Starck as a commercial supplier of cells and ceramics solutions, and the Fraunhofer Society with its Dresden based Institute for Ceramics Technology and Sintered Materials (IKTS).

Like any automotive product, an APU SOFC stack has to meet challenging cost targets, whilst at the same time has to conform to highest standards in function and reliability. The automotive industry has the respective well-structured and proven processes at hand to solve this target conflict. In the following sections, it is described how the automotive industry development process model was applied by Webasto to address producibility and electrochemical optimization of the SOFC stack at the same time. First, the process model is described in general and then selected system and process engineering aspects are highlighted using an interconnector plate as an example.

STACK DEVELOPMENT PROCESS MODEL

Technical Constraints

The Webasto stack is designed top-down, i.e. the detailed specifications are based on technical and commercial requirements defined by the APU system (1). Selected technical constraints derived from the APU specification that affect the stack design include:
• A rugged design with a high volumetric power density was needed. It could best be achieved with a planar stack configuration. Furthermore, the tight packaging of the APU system required a high degree of functional integration of every component.

• The stack overall pressure drop on the fuel as well as on the air side was not allowed to exceed 10 mbar. This constraint comes from the system philosophy that requires simple and thus fail-safe BoP components.

• The anode offgas outlet had to be separate from the offgas afterburner to allow for high fuel utilization in the stack, anode recycling and greater flexibility in thermal design.

• The usage of infrastructure diesel in the APU’s dry CPOX reformer raised questions regarding soot formation and sulphur tolerance. For thermodynamic reasons, thus a stack temperature above 800 °C was preferable, although at first sight this seemed to be in contrast with numerous attempts to lower the stack’s operating temperature.

Commercial Constraints

On the commercial side, the extensive market knowledge of Webasto as an automotive supplier active both in the OEM as well as in the aftermarket business was employed to develop a detailed cost and supply chain model. Based on well known sample stack designs from both the SOFC and the PEM world, the cost structure of a stack was broken down to the basic materials and processes. These sample stack designs were solely based on abstract geometric dimensions and volumes of components, i.e. no concrete stack design was preferred in the commercial calculations. Volume adjusted prices for raw materials, manufacturing process steps and energy were introduced into the model as parameters. The allowable cost of manufacturing, in contrast, was defined by estimated achievable market prices of APUs in various market segments and volume scenarios (see also (2)). Upon parameter variations, it became clear that it is possible to manufacture commercially viable SOFC stacks, although under severe restrictions, such as:

• Usage of ceramics components needs to be strictly confined to electrochemically active parts. Structural components need to be manufactured from steel.

• A high degree of automation is needed during assembling and testing the stack. More than 80% of the process operations need to be automated even for production figures of less than 100 stacks per year.

• The parts count in the mass producible stack needs to be drastically reduced as compared to state-of-the art designs.

Combination of Methods

Figure 1 depicts the principal scheme of methods that were applied during the stack design. The 3D data set of the stack and its components generated by 3D design software
acted as a central hub. The data did not only reflect the three dimensional shape of the components, but also their functional dependencies.

All requirements to the stack components coming from the electrochemical optimisation, flow dynamics and thermodynamics, producibility and production quality were bundled in the 3D-CAD data base.

At the same time, not only the final manufacturing drawings for parts and tools were generated from the 3D data base, but also input files for CFD and thermomechanical simulations. The built-in versioning functionality helped to correlate minor modifications to design features to the respective versions of parts. Since also functional dependencies between stack components are stored, common automotive industry quality tools such as failure mode and effects analysis (FMEA) can easily be conducted.

Figure 1. Scheme of methods that was applied during the stack design phase.

DERIVATION OF DESIGN FEATURES

In the previous section, several design guidelines were described that had been derived from technical and economical constraints. In the actual stack design phase, the overall stack concept as well as single components were designed according to these guidelines using common 3D CAD and simulation tools. Additional design processes common in the automotive industry were also employed, such as the involvement of production engineering early on. The welded hollow steel cassette that serves as an interconnector plate in the Webasto stack will be described as a typical example. Table 1 lists the requirements of this stack component along with its concrete design process and features.
Table 1: Selection of abstract requirements for the stack design and their concrete design features in the stack.

| Requirement (technical, commercial, functional) | Design feature |
|-------------------------------------------------|----------------|
| Limitation of ceramics usage to active components | Several commercial and proprietary ferritic alloys were selected as candidates for passive parts |
| High volumetric power density                    | Optimized arrangement of internal gas manifold lead-throughs and active area, avoidance of dead areas |
| Functional integration                           | Interconnector integrated flat plate heat exchangers serve as air preheaters and keep thermally induced stress away from the MEA |
| Pressure drop per plate less than 10 mbar        | 1. CFD optimized spacing and flow field in the hollow interconnector and between the levels 2. Open cathode design reduces pressure drop and facilitates even temperature distribution along stack |
| Separate fuel offgas outlet                      | At least one internal gasketed lead-through per plate for offgas |
| High degree of automation during assembly        | 1. usage of deep-drawing to shape the raw sheets ensures consistent quality 2. usage of overlap laser welding to join the cassettes from two steel parts for its low requirements to positioning precision 3. interconnector possesses several features that allow automated assembly equipment to grip or position plate or check its correct spatial orientation |
| Low parts count                                  | 1. interconnector has only two lead-throughs for gas, cathode was left open 2. identical parts (gaskets, spacer) within one interconnector cassette |

The industry standard 3D modelling tool CATIA V4 was used for modelling, drawing and versioning. Thermal and CFD (computational fluid dynamics) simulations were carried out using Comsol StarCD. Per plate, a hybrid grid with $1.2\times10^6$ cells (tetraeders, prisms, polyeders) was used. The relatively short time to solve each case (20 to 60 minutes on an 8-way 2 GHz AMD Opteron cluster) allowed multiple optimization loops.

Deep drawing of flow fields and other interconnector features required a thorough understanding of both the material, i.e. ferritic steel alloys, and the drawing tool. To identify allowable deformation degrees and critical geometries on a deep-drawn plate, a test tool was designed and built (see Fig. 2). It contained typical interconnector plate geometries in graded levels of sharpness and deepness. The test tool gave a standardised measure of maximum aspect ratios and feature dimensions in the interconnector candidate materials and thus for the 3D CAD of the deep drawing tool.
Figure 2. Standardized deep drawn test sheet of interconnector material used to measure allowable deformation degrees and feature geometries.

A major aspect when designing the plate was geometric tolerance and the respective tolerance chains. Geometric precision in deep-drawing and subsequently laser welding can only be achieved in certain limits, considering the given cost frame. Tolerances in the geometric dimensions of a deep-drawn part can occur for instance from a poorly definable "spring-back" behaviour of the sheet metal in the press, that itself is affected by the material's plastic-elastic behaviour, its surface texture etc. Several features of the interconnector plate, such as uniform anode gas and air distribution, rely heavily on the precise reproduction of flowfield and plate geometries (see (3)). To study the effect of deviations from theoretical perfection, well-known tolerances for deep-drawn parts were subjected to a CFD analysis. As a typical result, the uniformity of gas distribution along the anode compartment in the cassette changed by +/- 20 per cent when the height of the anode compartment was changed by only +/- 10 per cent. Thus, respective tolerance reserves were provided in the geometric design. The deep-drawing tool has a modular design to allow a flexible change of single design features without the need to build a new tool for each change.

As the last major manufacturing step, the interconnector plate is laser welded. The welding process makes relatively high demands to the joining partners in terms of surface quality, geometric precision and gap dimensions. These parameters were treated in principle like in the deep-drawing section: technological experiments were carried out to find optimum values for laser beam power, beam velocity and heat transfer. In parallel, the micrometallurgical effects in the interconnector were studied with respect to geometrical change and phase changes. Again, in several iteration loops, the welding tool as well as the welding process was refined to reach an optimum in terms of cycle time, seam quality and allowable plate warpage.

At the end of the design process, an optimized APU stack interconnector plate could be presented that meets the technical requirements, while at the same time holds great potential to be producible within a reasonable and commercially viable cost frame. The
plate (see Fig. 3) was used as an example to highlight the Webasto design approach. The same methodology was applied to all parts the stack consists of, i.e. gaskets, spacers, manifolds, MEAs and passive balance of stack components.

Figure 3. Complete assembled and welded cassette.

The stack underwent intensive testing on test benches as well as in a real APU system context. Results from these real world experiences will be worked into the stack design in a similar way as described above.

CONCLUSIONS

It was shown how common automotive industry procedure models can be used to overcome the target conflict between optimum electrochemical functionality and cost effective production of an SOFC stack.

The stack’s technical requirements were not based on the actual possibilities and limitations of an existing stack design, but instead were derived from the APU system functionality and APU customer expectations on a rather abstract basis. The commercial boundary conditions for the stack manufacturing were set from a similarly abstract cost model that was based on common principles found in all SOFC and PEM stacks and that covered the whole supply chain starting with ceramic powders and sheet metal coils.

The complexity of the design process was managed by adopting common industry procedures, such as target costing based on a value analysis, supply chain management, a complete 3D based design and simulation chain and incorporation of production engineering aspects very early in the design phase at the example of a bipolar plate.
ACKNOWLEDGEMENTS

The Webasto stack is developed in a joint effort together with H. C. Starck and the Fraunhofer IKTS. The author wishes to thank all colleagues in the stack teams at Webasto, HCST and the IKTS for their efforts and dedication. The work at Webasto's Neubrandenburg facilities is supported by the European Union under the terms of the European Fund for Regional Development.

REFERENCES

1. C. Wunderlich, 2004 f-Cell Forum, E2, Peter Sauber, Stuttgart, Germany, (2004).

2. E. J. Carlson, S. Sriramulu, Y. Yang, and W. P. Teagan, 2004 Fuel Cell Seminar, Courtesy Associates, Washington, D.C., (2004).

3. J. Ge, J. Han, and H. Liu, 2004 Fuel Cell Seminar, Courtesy Associates, Washington D.C., (2004).