Automotive Fuel Cell Stack Cluster Initiative for Europe II

Informe

Información del proyecto

AUTO-STACK CORE

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Proyecto cerrado

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Final Report Summary - AUTO-STACK CORE (Automotive Fuel Cell Stack Cluster Initiative for Europe II)

Executive Summary:
In this project automotive OEMs, component suppliers and research organizations are closely cooperating to develop an automotive PEM fuel cell stack platform. The technical concept is based on the Auto-Stack assessments carried out under an FCH JU Grant Agreement from 2010 to 2012. It sug-gests a stack platform concept in the power range from 10 to 95kW with the aim to substantially im-prove economies of

scale and reduce critical investment cost for individual OEMs and component suppliers by sharing the same stack technology for different vehicles and vehicle categories. The stack can also be used in several non-automotive applications. The platform concept thus is address-ing one of the most critical challenges of early fuel cell commercialization by generating and exploring scale effects to reduce cost. The final target of the project is the development of a stack having a nominal power of 95 kW at an operating temperature of 68 °C and an operating pressure of 200 kPaabs will be developed.

In the first reporting period, the specifications of the stack have been reviewed and updated. Evolu-tion 1 components for a 331 cell stack and several 10 and 20 cell short stacks have been manufac-tured. Furthermore, a testing program for the stacks has been agreed upon.

In the second reporting period, the Evolution 1 stacks have been manufactured as short stacks and in full scale for extended testing. The test results showed that 11 out of 13 design parameters have been achieved. The stacks showed robust and almost identical operational behavior at short stack and full size stack level, no fundamental design shortfalls have been identified.

In the third reporting period, the evolution 1 design was substantially refined and optimized. The evolution 2 design took the challenges identified during Evolution 1 design, assembly and testing into account. Particular emphasis has been given in improving flow characteristics, reducing weight and volume to achieve the technical goals set out in the description of work.

During the design process, cell pitch and footprint were reduced significantly. a much more compact stack design was realized. In comparison to stack Evolution 1, the volume shrank to 27.7 l, a decrease by 19%. The weight of the 335 cell evolution 2 stack was reduced to 33.1 kg, a reduction of 29%.

Extensive flow modelling allowed to substantially improve reactant flow homogeneity in the active area. Furthermore, the temperature spread in the cooling area was reduced. Short stack and full size stack testing clearly showed improved performance levels.

Stack Evolutions 1 and 2 had to undergo extensive automotive test cycles with respect to perfor-mance, endurance and robustness vs environmental conditions to demonstrate achievements and identify potential for further improvement.

It has to be noted that evolution 2 testing used an inert gas content of 30% at the anode inlet to take anode gas dilution in automotive system operation into account. During the test program, robust operation, freeze start capability, resistance to shock and vibration as well as endurance under dynamic load operation has been tested.

The peak power density of the evolution 2 stack was found to be more than 4 kW per liter under the fixed operating conditions selected as reference for this project thus establishing best of its class stack technology when compared to published performance data in the literature.

After completion of Evolution 2 testing, it can be concluded that with slight deviations in performance and degradation, all specification requirements of the project were met or exceeded.

Evolution 2 stacks are available as prototypes (S3) from Powercell. As a follow-up a German national project to further advance the stack design towards industrialization involvin 4 OEMs, 5 component suppliers and research organizations has been started in 2017.

Project Context and Objectives:

“Auto-Stack Core” establishes a coalition with the objective to develop best-of-its-class automotive stack hardware with superior power density and performance while meeting commercial target cost.

The project consortium combines the collective expertise of automotive OEMs, component suppliers, system integrators and research institutes and thus removes critical disconnects between stockholders.

The key objectives for the project are:

- Development of an automotive PEM fuel cell stack based on agreed OEM system requirements,
- Performance and durability compatible with the stringent requirements of the automotive industry,
- Use of proven technology which can be manufactured in an industrial scale reflecting in depths supply chain and technology assessment,
- Platform concept compatible with different vehicle categories and OEM platforms to allow combining of volumes,
- Technical concept with clear pathway to addressing stack target cost.

The ultimate target of the project is the establishment of a European response to the global technology progress by providing a competitive stack product that can be accessed and shared by several OEMs for their individual system integration work and vehicle platforms. The project is building on the achievements of Auto-Stack (FCH-JU GA 245142) and is moving them to the next phase. Within the project innovative material and component solutions were benchmarked and the most promising tested experimentally. Test results were compared to different design options and manufacturing approaches known from literature research. To further reduce stack and component cost, the technical development work was accompanied by a detailed cost analysis using tools established in the automotive industry.

Project Results:

Overview

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During the design process, cell pitch and footprint were reduced significantly. A much more compact stack design was realized. In comparison to stack Evolution 1, the volume shrank to 27.7 l, a decrease by 19%. The weight of the 335 cell evolution 2 stack was reduced to 33.1 kg, a reduction of 29%. The progress is clearly visible in the comparison of full size stacks.

Improvements

- Improved active to passive ratio and lower cell pitch gives lowered stack volume
- Improved material usage gives lowered weight
- Lower cost materials chosen for some balance of stack components
- More rugged housing design
- CVM electronics integrated in stack housing
- Implementation of prototype tooling for key stack housing components

The following figures are giving a comparison of objectives and achievements

Specification Unit objective Evo 1 Evo 2

Outer dimensions (length x width x height dm 6.5x4.3x1.8 5x4.3x1.8 4.1x1.5x1.49
Volume of the stack exterior dm^3 < 55 34.3 27.7
Weight without fluids kg <44 46.3 33.1

Extensive flow modelling allowed a substantial improvement of reactant flow homogeneity in the active area. Furthermore, the temperature spread in the cooling area was reduced. Short stack and full size stack testing clearly showed improved performance levels.

Targets and reference conditions

Strategic Analysis and the DoE have published updates of the Fuel Cell System Cost Analysis in 2015 and September 2016. The 2016 report assumes an 80kWnet electric fc system for automotive application with a nominal lifetime of 5000h. The annual manufacturing rate is up to 500 000 systems of a top selling model. The AutoStack-Core assessments in comparison refer to a 95kW fc stack power, which is comparable to an 80kWnet electric fuel cell system when calculating parasitic losses in the order of 15%. The ASC production rate was set at 30 000 stacks/year to better reflect and focus on the reality of lower production numbers in the early years. The requested ASC lifetime of 6000h is somewhat more demanding than the DoE target.

The fc system operating pressure of the SA/DoE report is 2.5bar absolute versus the AutoStack system requirement of 2.0 bar for max continuous power and 2.7bar for max peak power. The nominal power density of the 2015 SA/DoE stack with 749mW/cm2 is significantly lower than the AutoStack- Evolution 2 status with 978/957mW/cm2 - see Table 1. The total platinum loading of the MEA in the 2016 report is given with 0.134mg Pt/cm2 based on a dispersed de-alloyed PtNi-catalyst versus the previous NSTF. The de-alloyed catalyst together with the low loading is assumedly responsible for the lower specific power compromising overall stack power density.

The AutoStack-Core Evo 2-Pt-loading status is 0.35mg/cm2. The Platinum price is set with $1,500/troy ounce equivalent to 31.1g or $48.23/g. In the previous reports we have used an exchange rate of 1.2$/€ equivalent to €40.19/g. For simplicity reasons and better comparability, the Platinum cost will be maintained with 40.00 €/g in the following analysis. The 2016 SA/DoE cost target @ a production volume of 30 000units/year is calculated with 35,20$/kWgross . It compares to <36.81€/kWgross of the Auto-Stack Core Evo 2 status for the same volume.

The AutoStack specification is substantially more aggressive in terms of power density than the DoE reference stack. It is more moderate on the MEA Platinum loading reflecting the physical and electrochemical constraints of the catalyst, component and stack design with the given current fuel cell technology. Higher power density reduces the stack cost at almost the same rate as the assumed by the DoE necessary reduction of the Pt-loading which is practically impossible to achieve with current technology if and as long as high stack power density matters. The ASC specification has established the priority of stack power density and following made trade-offs between different conflicting objectives.

Stack performance

Stack Evolutions 1 and 2 had to undergo extensive automotive test cycles with respect to performance, endurance and robustness vs environmental conditions to demonstrate achievements and identify potential for further improvement. It has to be noted that evolution 2 testing used an inert gas content of 30% at the anode inlet to take anode gas dilution in automotive system operation into account. In stack evolution 1 a slight improvement in area specific power density over the 2012 state of the art could be

achieved while a major improvement in volume specific power density was reached by reducing the cell pitch from 3 mm to 1.2 mm when moving from graphite composite bipolar plates to the metallic evolution 1 design. In stack evolution 2 not only a major reduction in volume and weight was accomplished, the measures taken to improve the flow conditions also resulted in a significant improvement in area specific power density. Furthermore, the stack design showed surprisingly low sensitivity on variations of stoichiometry and reactant humidification. As a consequence, the peak power density of the evolution 2 stack was increased to more than 4 kW per liter under the fixed operating conditions selected as reference for this project thus establishing best of its class stack technology when compared to published performance data in the literature.
Nissan: 2.5 kW/l
Honda: 3.1 kW/l
Toyota: 3.1 kW/l
ASC evo1: 2.9 kW/l
ASC evo2: 4 kW/l
Besides increasing the power density, reduction of noble metal loading is a key factor in reducing fuel cell manufacturing cost. A second generation of MEAs having reduced the platinum loading from 0.5 mg/cm^2 to 0.35 mg/cm^2 was developed and tested. Its performance was found comparable to the state of the art. It is obvious that the stack using MEAs with an alloy catalyst at 0.4 mg/cm^2 has advantages in low and medium current density operation while MEAs using a pure platinum cathode catalyst and noble metal loading of 0.25 mg/cm2 show identical performance under peak load conditions.
Evolution 2 MEA also show comparable performance to benchmark MEAs from outside the consortium operated in the AutoStack-CORE hardware under neat hydrogen. Comparable performance is achieved. It has, however, to be noted that the AutoStack-CORE MEA had a cathode loading of 0.25 mg^/cm^2 as compared to the benchmark MEAs having a cathode loading of 0.30 mg/cm^2. The overall loading of all MEAs was 0.35 mg/ cm^2. Extrapolation of the curve gives an expectation value of slightly more than 0.6 V @ 2.0 A/cm^2 which is in line with results recently reported from the FCH-JU project VOLUMETRIQ.
Concluding the test results and lessons learned further improvements are possible when optimizing the stack operating conditions and some of the design elements. For example, when dynamically adjusting pressure and stoichiometry as a function of stack load, performance improvements are recognized. Particularly at high current load of 1.9 A/cm^2, a voltage gain of more than 40 mV per cell could be achieved.

Stack Endurance
When assessing stack lifetime of for automotive applications, 10% of nominal power loss are considered acceptable within a period of 6 000 operating hours corresponding to a vilatge loss of 11 µV/h. The target value for AutoStack-CORE according to the description of work was set tu 12 µV·h-1 under a dynamic load profile. As state-of-the-art, EPRI reports 2 500h stack durability corresponding to d degradation rate of 27 µV/h.
In This project, stack endurance testing was carried out according to a proposal from the European project Stack-Test (FCH-JU GA 303445) since there are no other commonly accepted testing procedures for stack endurance testing. A Fuel Cell Dynamic Load Cycle (FCDLC) current load profile used where 100% load is corresponding to a current density of 1.5 A/cm^2. The FCDLC contains 35 steps and has a duration of 1 181 sec including 36 sec of zero load (open circuit voltage). The profile is repeatedly applied to the stack under test using AutoStack-CORE reference operating conditions. At pre-determined intervals, the

test is interrupted and the stack is subject to a conditioning procedure.

A total of 5 short stacks and one automotive sized stack using MEAs developed within the project as well as one short stack using a benchmark MEA were subject to endurance testing the longest test lasted for more than 3 000 operating hours. Clear distinctions can be made between reversible and irreversible losses. When approximating the irreversible losses by the slope of a tangent to the bottom of the curve, a decay rate of 22 µV/h is found for the nominal load (450 A corresponding to 1.5 A/cm^2). However, it is also seen that degradation is not a strictly linear process. Load interrupts can result in a dramatic, yet short lived improvement in performance.

In parallel to the 3 000 h endurance test, a 10 cell short stack using a benchmark MEA was tested under the same operating load profile for 1 000 h. AutoStack-CORE reference operating conditions were used except that the stack was operated on neat hydrogen. A degradation rate of 18 µV/h was observed under nominal load conditions. After continuous operation for 1 000 h, the stack was taken to a different laboratory and the test under neat hydrogen continued for another 200 h where the degradation rate could be confirmed. A subsequent test under 30% N2 in H2 showed a slightly increased degradation rate. Hence, when operating the Evo2 MEA and the benchmark MEA under comparable operating conditions, the results are more or less identical.

System level tests under fuel recirculation over 1 000 h generally confirmed the results presented above. However, this test showed phases where the degradation rate was as low as 13 µV/h. As a summary, endurance tests carried out so far showed degradation rates in line with the findings of the EPRI study. Indications on the influence of operating conditions were found and need to be further investigated. Further studies are needed to establish a clear correlation of their influence and further mitigate the influence of unfavorable operating conditions.

Freeze Testing

The specification requirement for freeze start was to deliver 50% of the stack power in < 30sec. Freeze starts were performed at -5°C, -10°C, -15°C, -20°C and -25°C.

During freeze start @ -20°C, the stack did deliver 50% of power within 12.8 sec. When the same test was executed at -25°C, the stack performance ramped up similarly but dropped after about 10 sec and needed 58 sec in total to deliver 50% power. The reasons need to be analyzed and evaluated but may likely be linked with initial heat and water management issues that can be addressed by support measures for stack freeze start.

The stack was neither pre-heated nor was there a specific start-up procedure for freeze-start conditions developed and applied as this was not part of the scope of project. While the result does not entirely fulfill the specification target, it is most certain, that the specification can be met if these two elements will be developed and in place.

Stack Cost

Cost engineering of the component, cell and stack design was a major element of the overall design work in the ASC project. Three cost assessments were carried out by an external service provider for Evo 1, Evo 2 and Evo 3, respectively. The reference volume for the cost assessment was chosen with 30 000 x 100kW stacks/year as combined volume of all OEMs and other than automotive applications for the initial market introduction.

The comparison of the three assessments show a good result of Evo 1, substantial cost reduction in the second design phase (Evo 2) and a slight further cost reduction in Evo 3. These reductions are the result of a focussed design approach and several subsequent design actions adressing cost issues that are described and summarized in Figure 5. Reduction of the Pt-loading of the MEA from 0.5mg/cm2 to 0.35mg/cm2 in Evo 2 substantially contributed to the achievement. The achieved excellent cost result was thus generated by a combination of increased stack power density and reduced noble metal use.

The direct stack manufacturing cost of 36.81€/kW (Evo 2) is calculated on rated gross power and compares to 35,20$ for an annual volume of 30 000 units of the SA/DoE analysis. The equivalent Evo 3 cost amounts to 35,30€/kW. Assuming an exchange rate of 1,1 ($:€), the ASC direct manufacturing cost is on target with the predicted cost of the SA state-of-the-art cost analysis.

The data of the SA assessment are based on laboratory single cell hardware and/or generic modelling assumptions. The ASC data reflect a real automotive stack design based on validated hardware that was assessed with automotive cost methodology.

The ASC approach did establish high stack power density as the central design target. This requires substantially higher single cell performance. In combination with the automotive durability requirements, the Pt-reduction potential is therefore limited based on state-of-the-art catalyst and MEA-technology. Though, the ASC Pt-loading is more than double of the SA assumption (0.35mg vs. 0.15mg) the specific cost is on level with the predicted by SA stack manufacturing cost while the durability target is still not fully achieved (even with the higher loading) based on the applied protocolls.

Considerations towards stack evolution 3

The stack evolution 2 testing results confirmed that the intended design improvements over evolution 1 were fully achieved. The flow-field design improvements led to higher power density, better operational stability and thermal management. Particularly, the short term peak load performance originally intended to be held for a maximum of 10 sec turned out to be stable for extended periods of time. Therefore, the consortium decided to move the nominal load for evolution 3 to 1.9 A/cm^2. To further improve thermal homogeneity of the cell, the bipolar plate design has been modified to maximize the coolant flow through the active area. Furthermore, the header sizes were further optimized to improve the cell to cell media distribution.

Manufacturing and industrialization

Based on the technical development results in stack evolutions 1 through 3, a stack manufacturing concept for an industrialized stack assembly was worked out.

The concept is based on pre assembling three main parts before the main assembly of the complete stack. The pre assembling of the three main parts are done manually, while the assembly of the complete stack is mainly done automatically.

After the stack has been assembled it will go through testing and commissioning. If no deviations are detected it will be packed. For stack failing in testing, a rework loop is planned.

Conclusion

The results of AutoStack-Core are demonstrating the value of collaborative projects that are based on real world specifications and supported by relevant industrial and research stakeholders. The assessments that were done in the predecessor project AutoStack have delivered key assumptions to determine the proper technical approach for the stack development in AutoStack-Core. The established focus on stack power density has delivered an outstanding contribution to the overall achievement of technical and cost targets.

The ASC stack design delivers a significantly higher stack power density as current Toyota and Honda stack designs. Based on substantial reduction of weight, volume and Pt-use through Evolutions 1 and 2, the cost assessments have provided evidence that the DoE 2016 target cost for a production rate of 30 000 stacks/year can be achieved. From all we know, this is a unique accomplishment. Equally important, the stack and component design is based on industrial manufacturing methods and can be conveyed into mass production ready designs in following development steps.

The stack platform concept facilitates the option of combining volumes of different OEMs and other than automotive applications to gain scale effects early and achieve target cost faster. Compliance with common 400V vehicle architectures as supposed to 600V in the Toyota concept (see 2nd benchmark report) reduces the specific component cost at system level and does allow industry wide scale effects. The ASC project thus has delivered a tool to strengthen European competitiveness in what is supposed to be a critical innovative technology.

The achieved stack durability deviates from the specification target but reflects the overall technology status. Based on the EPRI analysis it is considered state-of-the-art – see Table 5. Further optimization of the stack design, MEA concept, of BPP coatings and stack operating parameters/characteristics will be needed to achieve automotive maturity. Full exploration of the performance potential of materials and components will moreover require development and implementation of mass manufacturing processes to deliver the scale effects in combination with the required consistent automotive quality.

The project results have attracted a lot of interest from new industrial stakeholders and the German government. After 18 months of preparation, the successor project AutoStack-Industrie was started in May 2017 that is co-funded by the German government in the framework of the National Innovation Program. Besides many previous actors, two new OEMs, Daimler and Ford, joined the consortium. The project will address the needed design steps towards achieving automotive product maturity and the development of mass-manufacturing technologies.

Stack evolution 2 is commercially available as a prototype from Powercell (S3-stack). Due its power density this stack has been selected as one option for truck integration with the U.S. company Nikola motors thus being a first example of a European stack selected for system integration in the U.S.

Potential Impact:

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List of Websites:
http://autostack.zsw-bw.de

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