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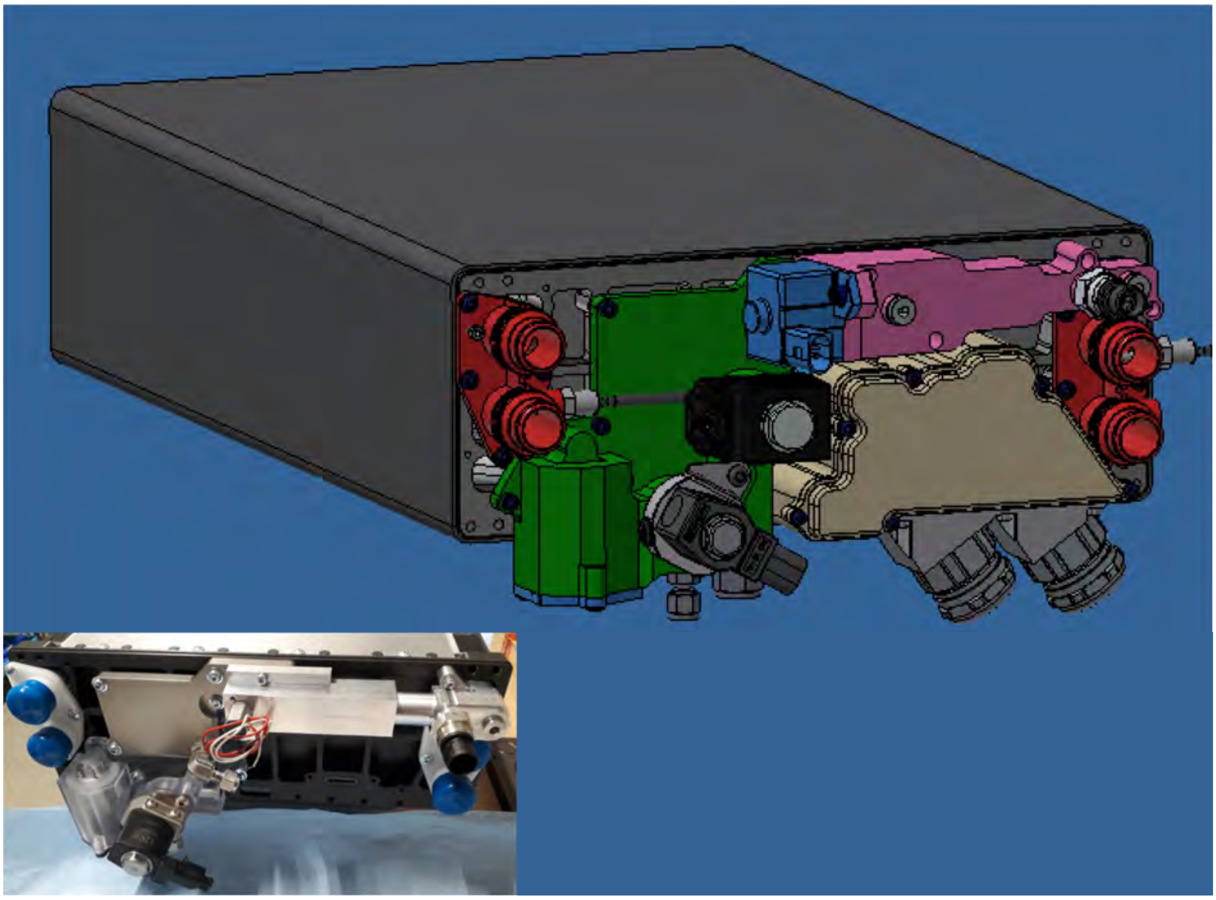
Final report

FC-Horizon

Novel fuel cell system for mobile applications



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Zusammenfassung

Der vorliegende Abschlussbericht beschreibt das Projekt FC-HORIZON und die in der bis Ende Oktober 2020 erweiterten Laufzeit erzielten Projektergebnisse. Ziel des Projektes war es ein neues Konzept für eine horizontal angeorneteBrennstoffzelle mit integriertem Anodenmodul zu entwickeln, erste Prototypen zu realisierun und in umfangreichen Tests zu validieren. In den Kapiteln 2 und 3 wird der Hintergrund und die Vorgehensweise erläutert, in den Kapiteln 4 bis 6 werden die Ergebnisse dargestellt und interpretiert und die nächsten Schritte definiert. Das Projekt wurde erfolgreich durchgeführt, fast alle Arbeiten der Arbeitspakete WP1 bis WP5 sind abgeschlossen. Die erzielten Ergebnisse werden in zukünftige Projekte und Produkte von Plastic Omnium, der neuen Muttergesellschaft von Swiss Hydrogen, einfliessen, insbesondere auch in die Brennstoffzellensysteme, die mit Stacks aus der Zusammenarbeit mit Elring Klinger realisiert werden.

Résumé

Ce rapport décrit le projet FC-HORIZON et ses résultats pendent la durée du projet qui était rallongé jusqu'au Octobre 2020. Le but du projet était de développer un nouveau concept pour un stack avec une orientation horizontale et avec un module anodique intégré ainsi que la réalisation des premiers prototypes et la validations de ces prototypes dans un programme de test extensif. Les chapitres 2 et 3 illustrent le contexte et la démarche du projet, les chapitres 4 à 6 contient les résultats, leur interprétation et les prochaines étapes. Le projet a été exécuté avec succès, WP1 àWP5 sont complètes. Les résultats vont être utilisé dans les futur projets et produits de Plastic Omnium , la société mère de Swiss Hydrogen, essentiellement aussi dans les systèmes pile à combustibles qui vont être réalisées autour des stacks de Elring Klinger.

Summary

This final report describes the project FC-HORIZON and shows the outcome of the entire project phase which has been extended until October 2020.The goal of the project was to develop a new concept for a fuel cell stack with horizontal arrangement and an integrated anode module, to realize several prototypes and to validate them in extensive tests. Chapters 2 and 3 explain the background and the approach as defined in the tender. In the chapters 4 to 6 the results which have been achieved are presented and discussed and next steps are outlined. The project has been carried out with success, WP1to WP 5 are completed. The results will be used for the development of future projects and products of Plastic Omnium the new mother company of Swiss Hydrogen, especially for the FC systems which will be built around the stacks from Elring Klinger due to the Joint Venture that has been created between Plastic Omnium and Elring Klinger in November 2020.

Main findings

- Scalable FC systems for various applications in future hydrogen mobility are urgently required
- Reliability and durability can be improved with new concepts for stack compression units and integrated anode subsystems
- Passive Hydrogen recirculation with ejectors is feasible over the entire working range of a FC system
- Air compressor, (integrated) humidifier and DC/DC converter are the most important “balance-of-plant” components and Swiss companies and research institutions can play an important role in the development and supply of there components.

Contents

Abbreviations

BOP	Balance of plant
BPP	Bipolar plate
CAD	Computer aided design
CFD	Computational fluid dynamics
CVM	Cell voltage monitoring
FC	Fuel Cell
FEM	Finite Element Method
HSL	Hardwired safety layer
MEA	Membrane Electrode Assembly
PEM	Polymer Electrolyte Membrane or Proton Exchange Membrane
PO	PlasticOmnium
PSI	Paul Scherrer Institute
RfQ	Request for Quotation
SH	Swiss Hydrogen
SFOE	Swiss Federal Office of Energy
WP	Work Package

1 Introduction

1.1 Background information and current situation

Following the acquisition of Swiss Hydrogen by the French group Plastic Omnium, one of the world leaders in the automotive industry, the strategy of Swiss Hydrogen has been refocused on fuel cell controls and balance of plant for mobility applications. Today, a very few number of hydrogen cars are on the road. However, due to the limitation in real driving range and charging time, logistic companies are pushing very hard to integrate carbon free vehicles running on hydrogen in their fleet.

Swiss Hydrogen has already developed two fuel cell systems prototype that have been integrated into vehicles used by logistic companies. One can mention a 10kW fuel cell range extender that has been put in operation in a Renault Kangoo ZE as well a 100kW fuel cell system integrated in the first hydrogen 34 ton delivery truck for Coop. Both project have demonstrated the full potential of logistic vehicles running on carbon free hydrogen. A 30kW system has also been developed for a solar boat, but its size and power is ideal for light delivery trucks below 3.5 ton. With these recent developments, Swiss Hydrogen is well positioned to address a wide range of hydrogen vehicles for the logistic industry.

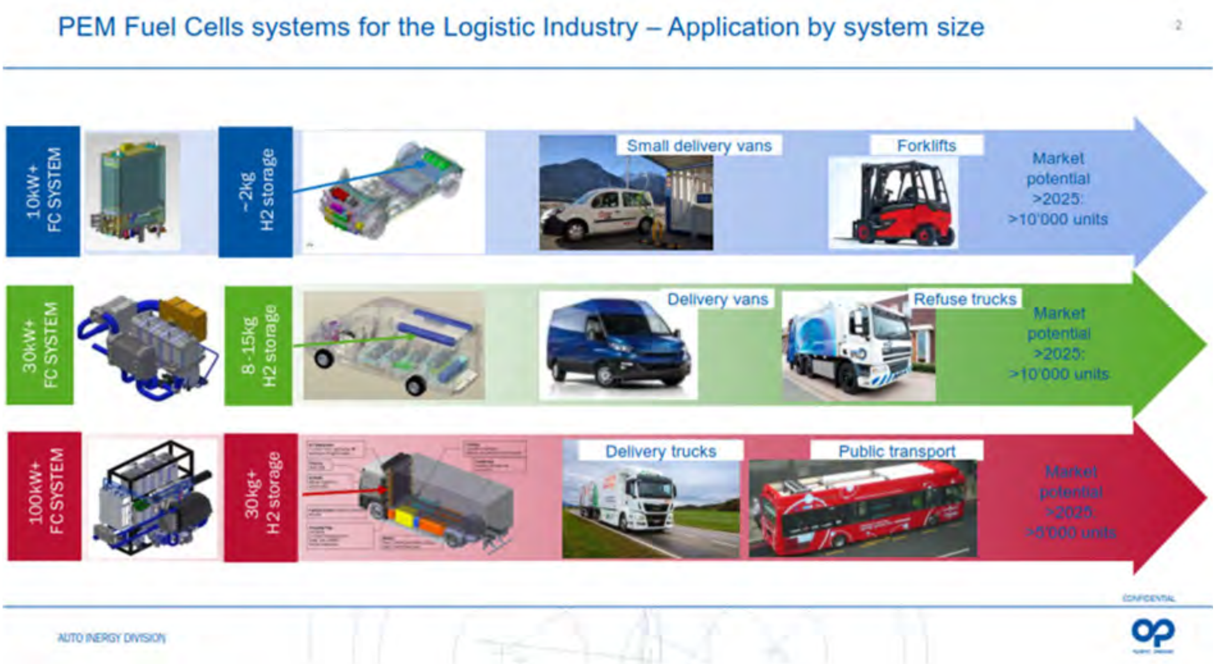


Figure 1: Example of fuel cell system size for different logistic vehicles

In November 2020 Plastic Omnium has announced a Joint Venture with Elring Klinger (EK) on the development and manufacturing of FC stacks and the acquisition of EKAT, a company working on the implementation of EK stacks into fuel cell systems in Austria, similar to the activities of Swiss Hydrogen. It was also announced that PO has the ambition to become a world leader in hydrogen mobility and to invest 100 million Euro per year into this technology over the next years.

Although at the time of writing this report it is not yet clear how the future collaboration between the teams in Fribourg, Dettingen (D) and Wels (A) will be organized it is obvious that future FC systems will be based on the existing EK stack technologies, NM5 and NM12. These stacks are built with metallic bipolar plates and have a very high power density. They can be scaled between 5 and 68 kW (NM5) respectively 25 to 135 kW for the NM12.

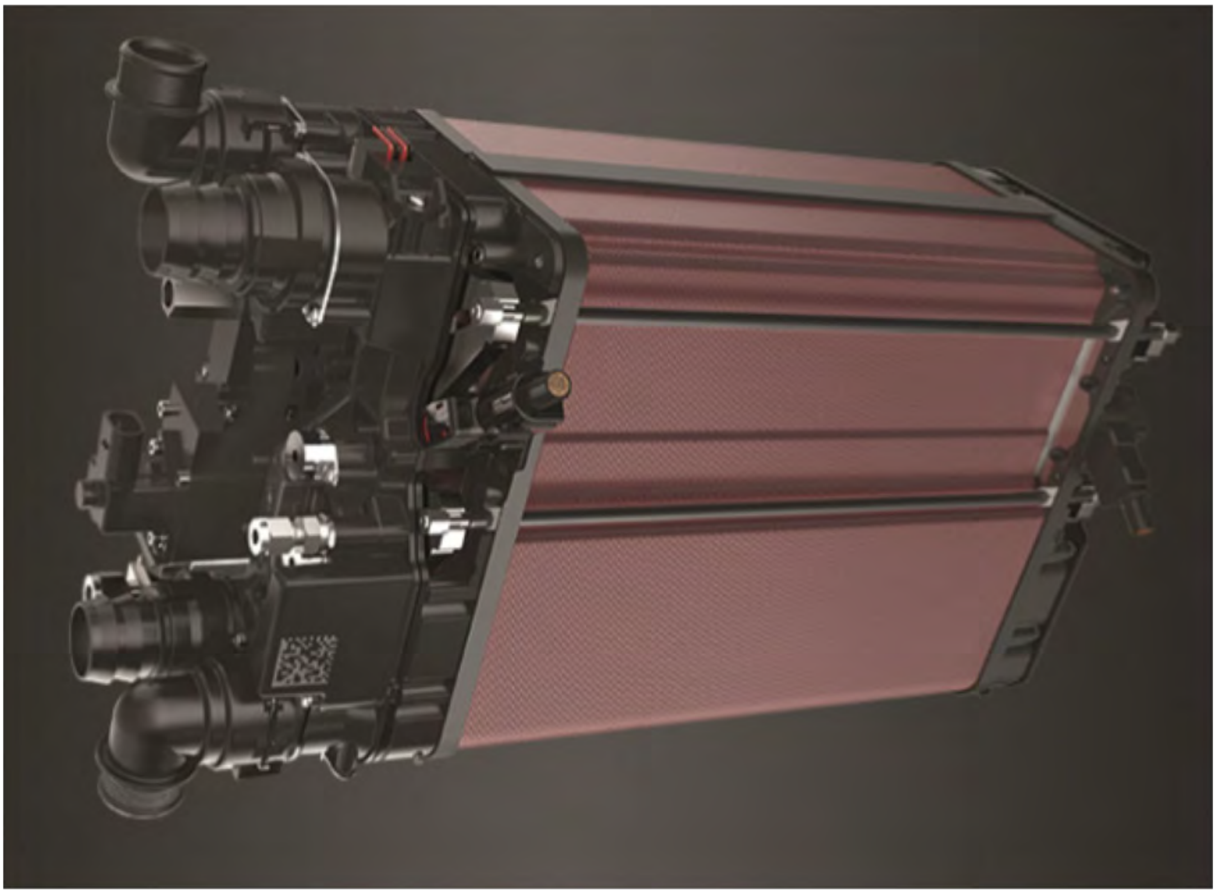


Figure 2NM5 stack from Elring Klinger

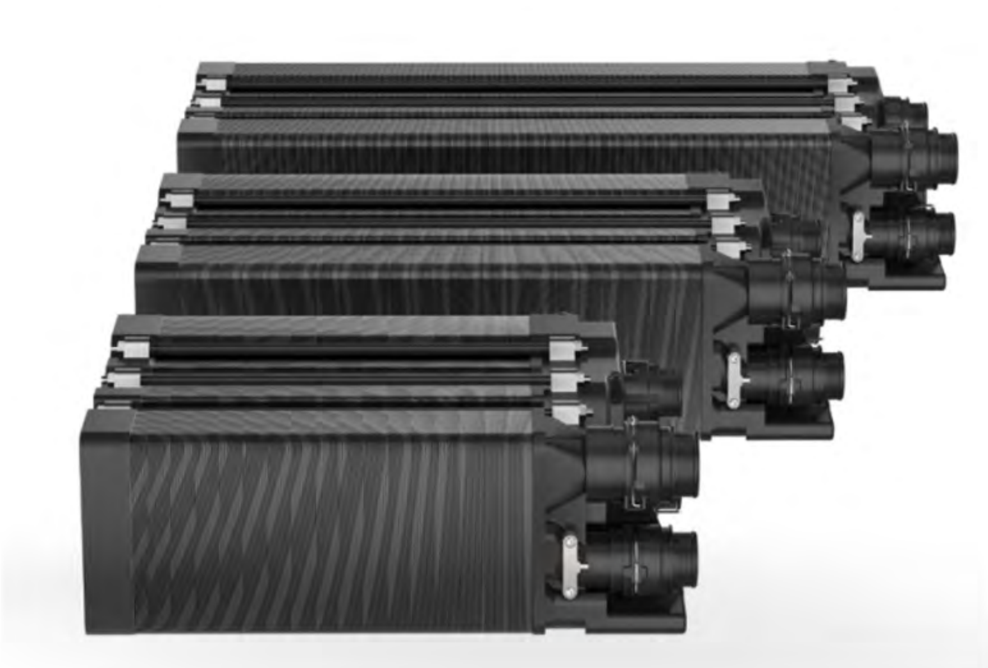


Figure 3: NM12 stack from Elring Klinger

For both stacks media modules are under development. These media modules contain anode water separation, anode drain and purge valves and several sensors. Preheating and recirculation of Hydrogen and H2 pressure regulation with proportional valves is not integrated yet. Once the official closing of the Joint Venture is completed (latest in spring 2021) the teams can come together and evaluate the technologies which are available in the different sites. The results of this project will be disclosed and there is a very high likelihood that the findings and technologies can be applied on the two stacks of EK.

The timeline of the development of the systems with different stack sizes is not fully defined yet but the 30kW system has the highest priority as there are immediate projects for light commercial vehicles in the RfQ phase.

1.2 Purpose of the project

The aforementioned running fuel cell systems also brought into light some fundamental technical challenges which remain and need to be addressed and solved prior to any commercialisation. These challenges are the following:

- Thermal management: due to its very low operating temperature (<80°C), the fuel cell is very sensitive to the coolant temperature and flow. Hot summer temperature require very large radiators and fast coolant dynamic to avoid cells overheating. On the other hand, cold winter temperature impose very precise coolant flow control to avoid water condensation within the stack (which induces cell degradation through hydrogen starvation). In both cases, thermal homogeneity of the stack is also of crucial importance.
- Water management: humidity control within the stack is of outmost importance to ensure enough membrane conductivity (sufficient wetting) while avoiding the risk of internal water condensation. Humidity levels in the cathode air flow is also very sensitive to the outside air temperature. Thus the stack humidity has to be measured and the air flow passing through the humidifier should be actively controlled. System water removal strategies and drying procedures to avoid icing in winter times are also absolutely necessary. Water removal on the anode loop is another challenge to solve with an optimum to be found between liquid water removal (possibly blocking hydrogen recirculation) and hydrogen purges (decreasing the system efficiency).
- Hydrogen recirculation: to optimise system efficiency with passive hydrogen recirculation over the whole power range of the fuel cell. Complete mechanical design integrating new automotive compatible components is necessary for every fuel cell system.
- Cell Voltage Monitoring (CVM): to avoid individual cell degradation (requiring full stack replacement) with the control of every cell voltage. Current CVM devices on the market are either too sensitive to potential transient cell status (negative cell voltage) or too bulky to be integrated within a vehicle system. Dedicated CVM electronics, including impedance functionalities for the drying process is not an option for successful commercialisation of reliable fuel cell systems. Some stack manufacturer and automotive OEM state that a CVM will not be required for FC systems in mass applications but we see the need for such a device to improve the operation stability under special conditions (start-up, freeze start, cold operation, highly transient operation, shut-down) and such to increase the lifetime of the FC stack. Especially for commercial vehicles this is of a very high importance. For both NM5 and NM12 stacks EK specifies that the use of a CVM is mandatory.

All these listed technical challenges have to be addressed in the context of another fundamental change. Until now, every fuel cell system developed by Swiss Hydrogen used vertical stack positioning as shown in the above picture. Recent discussions with different OEM’s highlighted the need for a horizontal stack system design in order to facilitate its integration into the vehicle.

1.3 Objectives

The target of this project is thus to develop a scalable PEM FC system with a power range of Power 10 to 30 kW DC net power. The efficiency shall be at least 48% at rated power and at least 58 % at peak efficiency. The durability shall be superior of 10'000 h under favourable operation conditions and a MEA exchange shall be possible at the end of the lifetime so that the bipolar plates with its seals can be reused. The compact height of the system (target < 150 mm) will be beneficial for underfloor vehicle integration.

Key automotive specifications shall be met such as operation in ambient temperature from -40 to +85°C, a protection class of at least IP67, typical shock and vibration requirements and compliance with EMC requirements.

The system shall contain the FC stack with cell voltage monitoring (CVM), the entire anode recirculation loop with purge and drain function, a junction box for the HVDC connection) and some sensors for cathode and anode loop.

The CVM will be a complete new development using the experience gained with the CVMs of the previous projects. The main improvement shall be the tolerance to negative voltages, a possibility to operate under start-up and shutdown conditions when the stack voltage is very low and a significantly higher reliability. A scalability shall be achieved since the CVM will consist of 1 master module and a flexible number of slave modules.

2 Procedures and methodology

The baseline of this project is the existing cell design with 200 cm^2 active area and compression molded graphite bipolar plates with integrated injection molded elastomer seals (see Figure 4). Several thousands of these plates have successfully been used in different applications. The robustness of the plates is excellent, the scrap rate at the manufacturer is very low, so far only two cells have developed a leak during assembly. During operation no leak has developed. A new stacking process has been established, where sub-stacks of 12 cells are pre-assembled and tested for leakage on a semiautomatic test-machine. An eventual crack in the bipolar plate a defect of a seal or of the MEA can be identified easily before the entire stack is compressed. Since this process is established all stacks have been defect-free. Figure 5 shows the assembly cell currently installed at the Paul Scherrer Institute with the automatic washing street on the left, the sub-stack test machine in the middle and the stack assembly press on the right.

Figure 4: Graphite bipolar plate

Figure 5: Stack assembly station at Paul Scherrer Institute

The FC system design is based on the existing 10 kW FC system as demonstrated in the Kangoo Range Extender (see Figure 6). Several key improvements have to be addressed in order to reach a system maturity that has a good chance to be industrialized. Passive hydrogen recirculation with two types of ejectors must function over the whole power range of the fuel cell. So far only an injector, which induces undesirable pressure pulses, and a recirculation pump, which limits the efficiency of the system, have been put in operation. A new control strategy using a new humidity sensor and a by-pass valve towards the humidifier has to be implemented in order to better control the humidity level within the stack and avoid cell flooding or drying. At the same time, water removal on the anode loop has to be optimized to avoid water ingress in the ejector. Thermal management and uniformity must also be fully revisited to enable smooth performance over a wide range of external temperatures. Another key change will be the orientation of the FC stack. Whereas for all the projects until now, the stack was oriented vertically with the manifolds connected on the bottom of the stack the new system shall have a horizontal stack orientation which is beneficial for

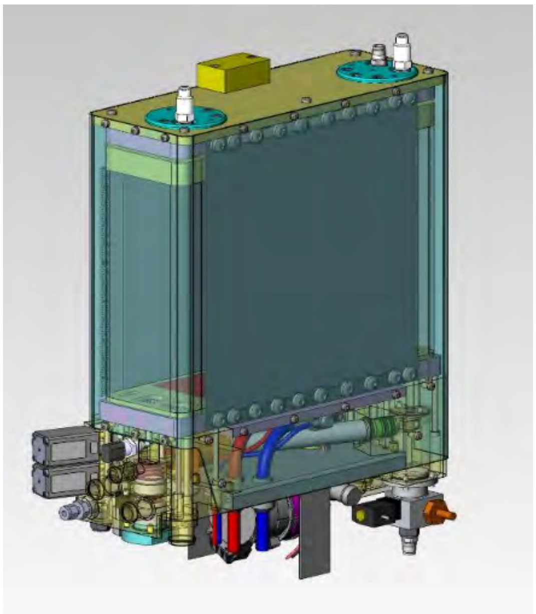


Figure 6: FC stack subsystem of Swiss Hydrogen's Kango Rex vehicle

several application especially when the FC system shall be placed into an underfloor compartment or in a forklift. New balance of plant components shall be integrated, especially the valves for the anode loop. In the previous systems standard industrial valves have been used but these valves do not fulfil automotive specifications (ambient temperature range, protection class, vibrations, maintenance and repair). In the meantime several components have appeared on the market and have been identified as suitable candidates for this new development.

This project has be divided into work packages consisting of:

WP1 FC subsystem concept

Conceptual work in 3D CAD for the new design of endplates with improved distribution of compression force and thermal homogeneity and the new anode recirculation loop with passive recirculation by ejector, allowing a combination of continuous and pulsed H2 flow, improved water separation, improved thermal design to reduce condensation.

WP2 FC subsystem design

The concept developed in WP2 will be optimized based on FEM simulations of deformation and stress as well as CFD simulations for the fluid flow and temperature distribution. In parallel test interfaces will be designed to be able to test subsystems (stack, anode module) individually. The final design will be detailed out in CAD, 2D drawings will be completed. A BOM will be created.

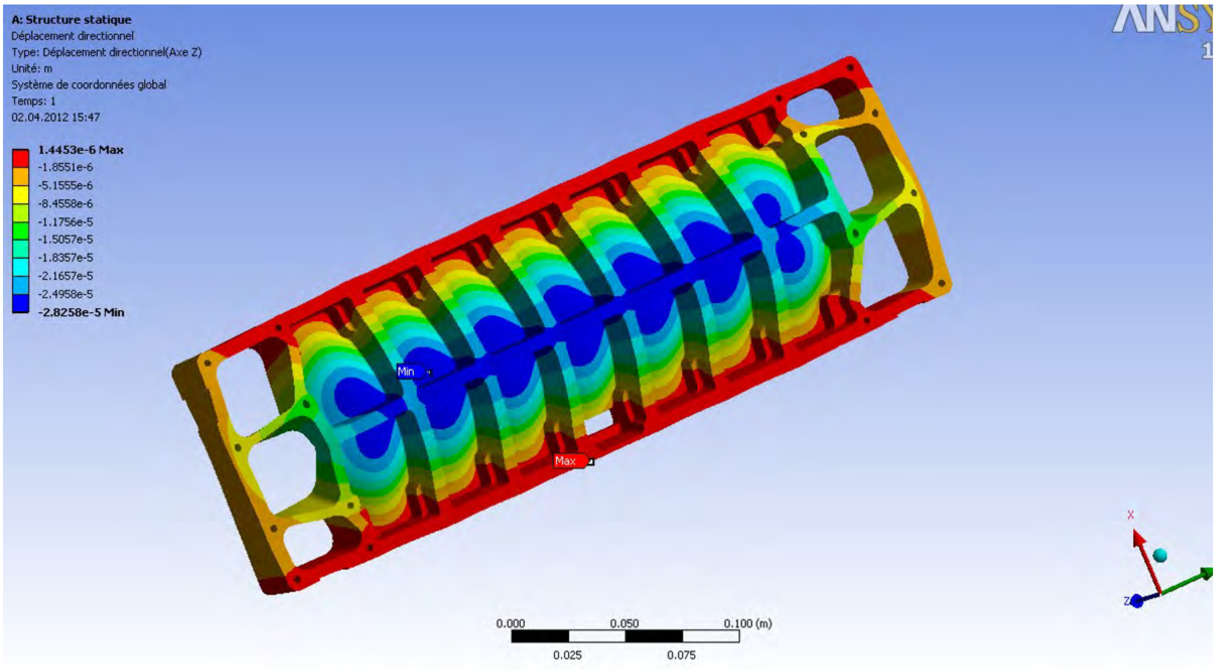


Figure 7: Example for FEM simulation of elastic deformation of end plate (existing design)

WP3 FC subsystem prototype realisation

One FC stack with approx. 80 cells will be assembled for the use in a 10 kW system and another stack with approx. 220 cells for the use in a 30 kW system. Several sets of system components will be manufactured, mostly by machining but some parts might be made from 3D printing.

The BOP components will be purchased and at least 2 systems will be assembled and tested with the corresponding test interface. Afterwards the systems will be mounted onto the 10 kW and 30 kW stacks and equipped with instrumentation sensors to prepare for the following testing on the new 100 kW system test stand in Swiss Hydrogen's labs in Fribourg.

WP4 CVM and HSL development

The cell voltage monitor (CVM) and the Hardwired Safety Layer (HSL) will be specified and several concepts will be proposed. After a concept evaluation phase the most promising concepts will be realized in a breadboard hardware to test the basic functionality and the compliance with the specification. With positive results a PCB layout will be defined and a set of first prototypes will be realized in hardware. In parallel the software will be developed and a test interface and a test bench will be designed and manufactured. Initial testing will be done to prepare the first usage in a running FC system.

WP5 Testing

Several short stacks (with 6 to 10 cells) will be assembled. Different MEAs will be characterized (U/I curves and sensitivity on operation parameters) and the most promising MEAs will undergo a durability test. One short stack will be equipped with a measurement device which allows to measure the local distribution of the current density over the active area. The short stack tests will be carried out in Swiss Hydrogen's labs in Fribourg and in the labs of PO-CELLTECH, a joint-venture company of Plastic Omnium in Israel.

The 10 kW stack and the 30 kW stack will be tested according to the test procedures developed in the EU-project "Stack test" http://stacktest.zsw-bw.de/media-centre/test-modules.html. The Modules 1-4, 7 and 8 shall apply.

The FC systems (stack with integrated anode modules) will be taken into operation together with the CVM and HSL developed in WP4. After basic functionality checks the systems shall demonstrate operation stability and reliable start-up and shut down behavior. The efficiency will be measured over the entire load range.

Several key components of the cathode loop shall be characterized on an air test bench (compressors from Celeroton, Fischer and Belenos and blowers from Micronel) and on a modified FC stack test bench (Humidifier from Fumatech).

The air test bench and the 100 kW FC system test bench are available, the FC stack test bench with a capacity to test up to 40 kW will be operational in February 2019. All of these tests will be carried out in Swiss Hydrogen's labs in Fribourg.

3 Results and discussion

3.1 WP1 FC subsystem concept

Figure 8 shows the first 3D design concept of the 10kW stack with 2x48 cells.

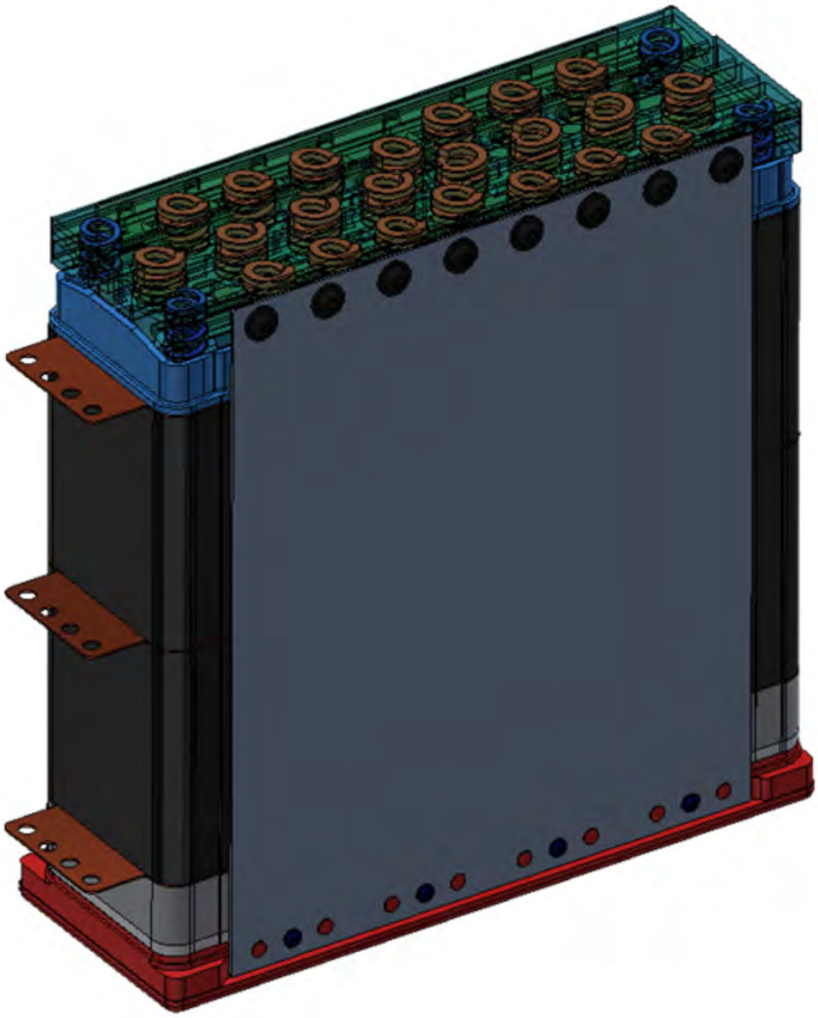


Figure 8: 3D model of FC stack with 2x48 cells and middle current collector

The stack compression design has been completely reworked from the previous version. The arrangement of the springs to maintain the complession of the stack has been optimised with several loops of FEM simulations. Figure 9 shows a local deformation of the plastic rear end plate with integrated pockets for the compression springs. The deformation is below 0.25mm which is an excellent value for a plate with a size of 110 x 360 mm and a weight of only 400 g.

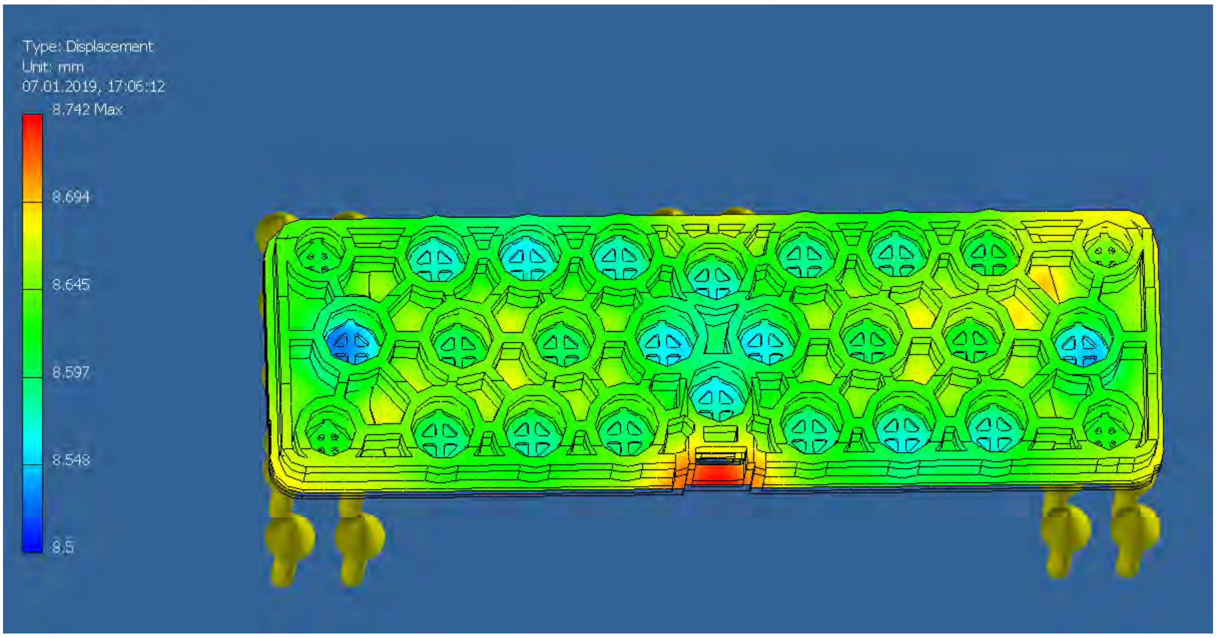


Figure 9: FEM simulation of rear endplate

It was decided to limit the content of the BOP components integrated into the endplate of the following two subsystems:

A: Anode Subsystem including Hydrogen supply, conditioning, recirculation, water seperation and water/hydrogen release

B: DC Bus including Bus bars, current sensor, terminals for cable lug connection, potentially also main contactor

The integration of the anode subsystem is very important as the thermal capacity of the Hydrogen flow is very small due to the low density of hydrogen (0.089 g/l vs. 1.29 g/l for air) and the small volume flow rate (280 Nl/min vs. 1300 Nl/min of air for a 30 kW fuel cell under typical operation conditions. As the thermal conductivity of hydrogen is relatively large the gas will quickly cool down and condensation will occur as soon as it enters external components which are not maintained to the operation temperature of the FC. Furthermore the pressure losses of the anode recirculation path have to be minimised as the efficiency of the ejectors decreases with an increasing pressure drop the ejector has to overcome.

The integration of the bus bars, the current sensor and the main contactor allows for cost efficient and compact solutions to maintain the FC stack water tight, dust tight and protected against electric shock (protection class IP67).

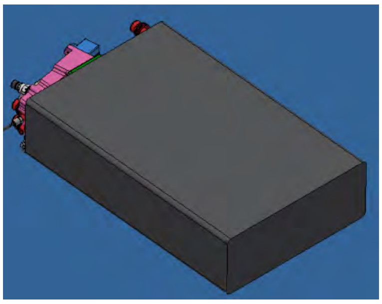


Figure 11: Housing concept

Figure 10: The housing is completely closed on the back side of the FC. A bus bar brings the plus pole to the front side junction box

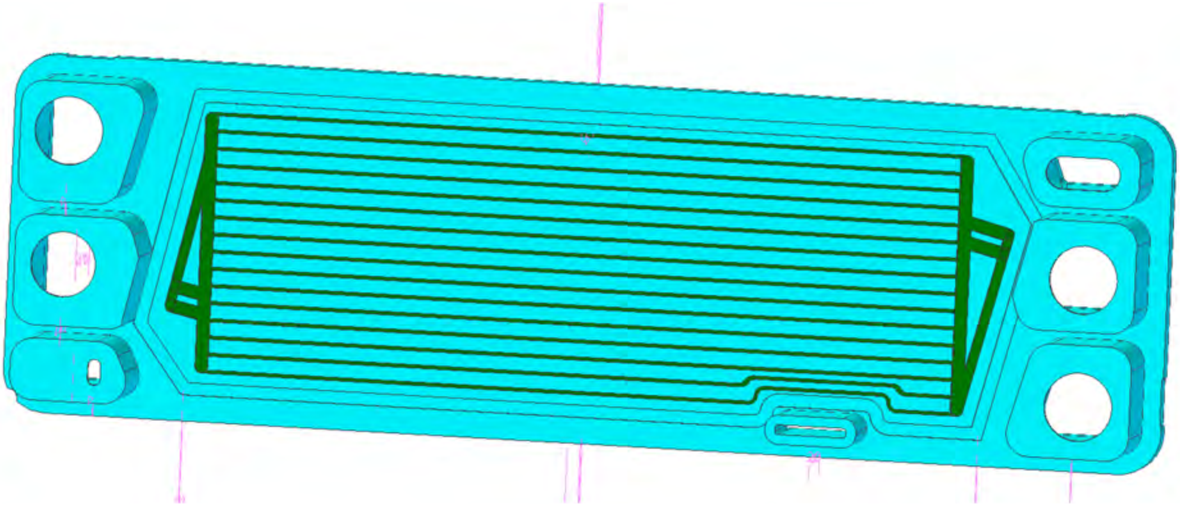


Figure 13: Integration of cyclone water separator and H2 preheater

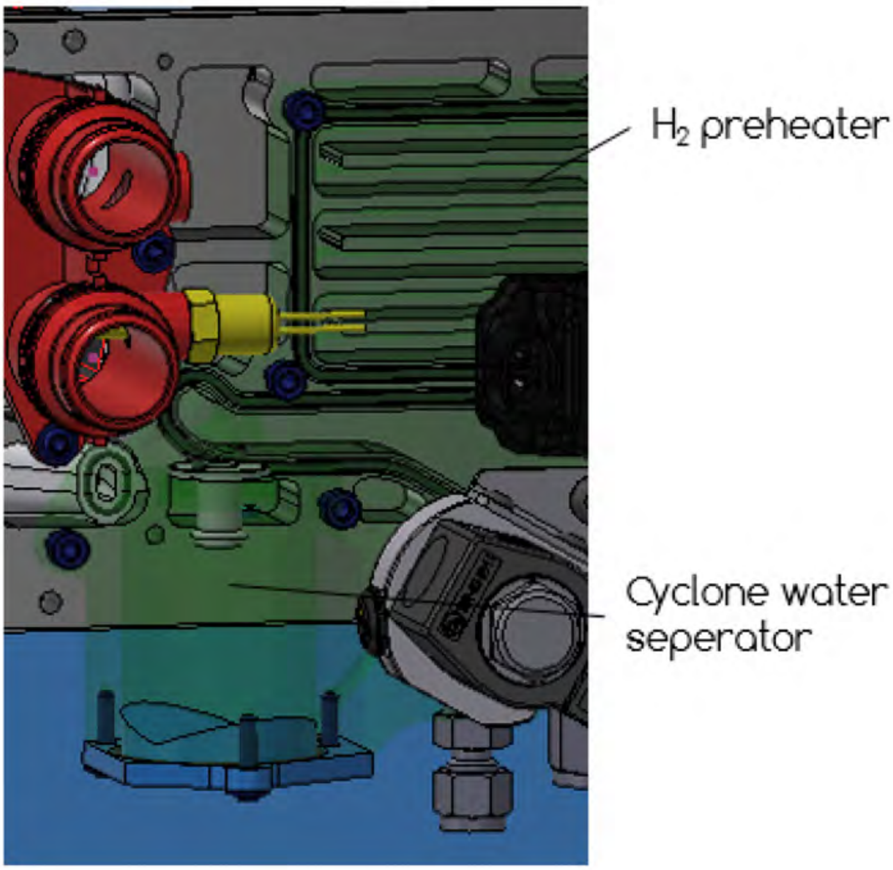


Figure 12: First draft of additional coolant channels in isolation plate to preheat front endplate

The space gained on the endplate compared to the 10 kW system for the Kangoo, where additionally the coolant pump and the coolant bypass had been integrated, can now be used to improve the arrangement of the anode loop components, their thermal coupling to the endplate and to add a heat exchanger to preheat the Hydrogen coming from the fuel tank to a temperature close to the operation temperature of the FC.

The endplate itself can be heated with a small bypass of coolant entering the FC stack. This bypass is distributed to the relavant area of the endplate by channels incorporated into the backside of the isolation plate. This isolation plate nests the current collector plate and isolates it electrically from the metallic endplate. The isolation plates will be made from a fiber reinforced plastic (e.g. PPS GF40) by injection moldings thet the additioal channels are cost neutral. Prototypes have been made by additive manufacturing (MJF).

3.2 WP2 FC subsystem design

After a few iterations of 3D design an optimised configuration could be found. The main elements can be seen in Figure 14.

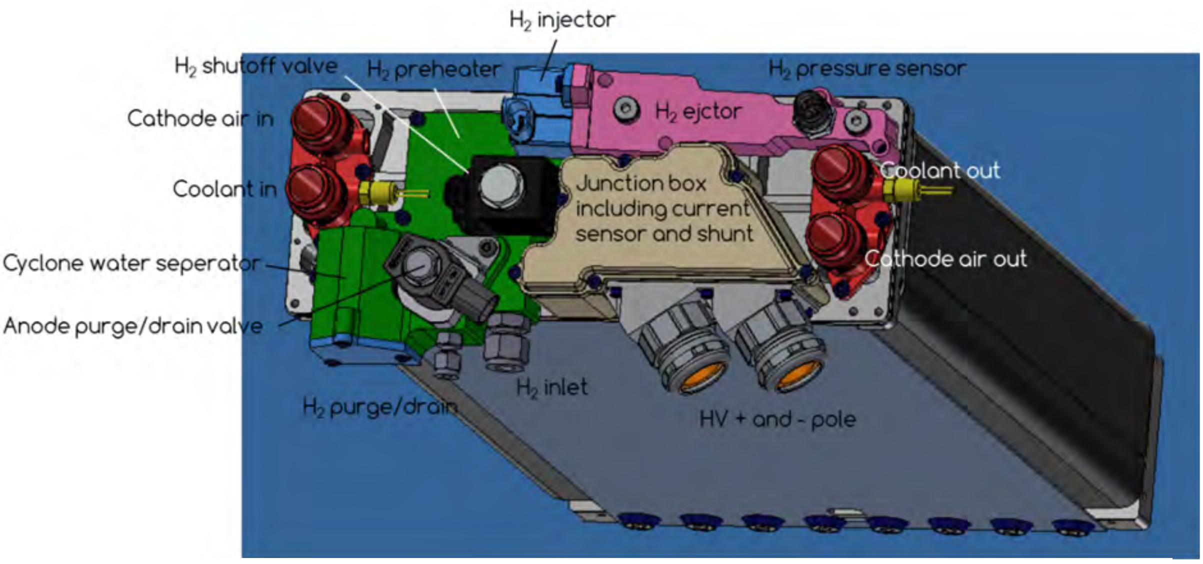
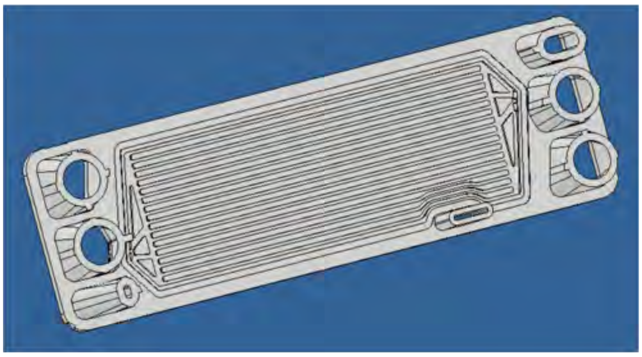


Figure 14: Content of integrated subsystem



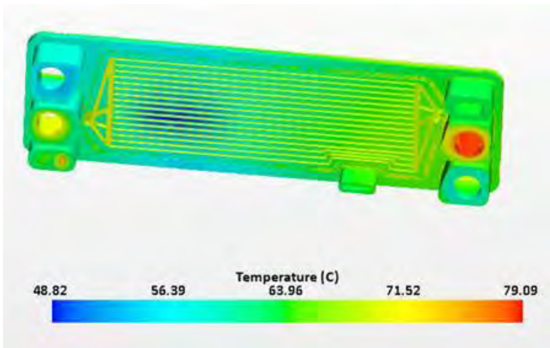


Figure 16: Final design of additional coolant channels in isolation plate

Figure 15: CFD simulation of temperature distribution on isolation plate/endplate interface

CFD simulation has been executed on the flowfield the isolation plate. The coolant inlet temperature was set to 70°C, the outlet temperature to 80 °C and the hydrogen inlet temperature to 0°C. The temperature distribution within the isolation plate could be improved by optimisation of the inlet channels, the distribution zones at inlet and outlet and the depth of the coolant chennels . The lowest temperature is in the zone of the H_2 heat exchanger but it is only 5°C below the inlet temperature of the coolant. The temperature profile in the coolant channels of the isolation plate and the optimised geometry is shown in Figure 16and Figure 15.

The temperature profile in the interface between the isolation plate and the first bipolar plate is shown in the following picture. The profile is following the temperature profile of the coolant flowfield in the bipolarplate with a deviation of maximum 2°C.

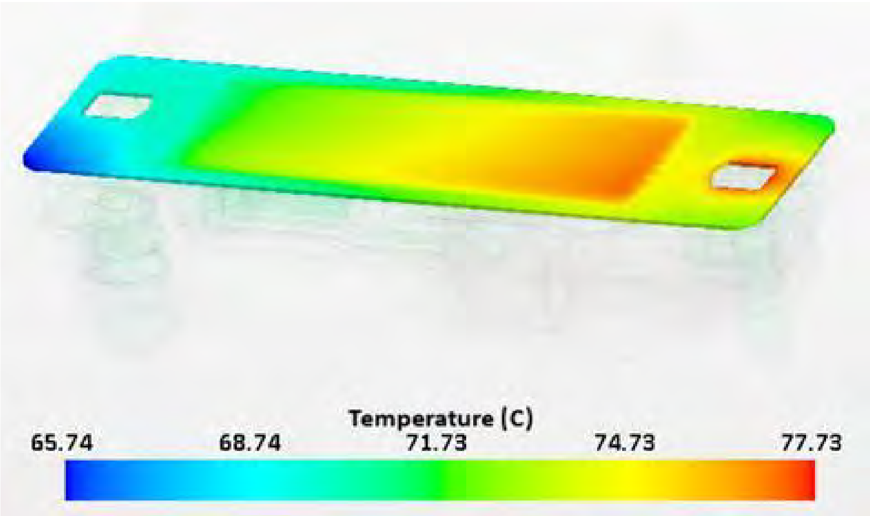


Figure 17: Temperature profile in interface between isolatio plate and first BPP

The effectiveness of the H2 heatexchanger could be proven in another CFD suimulation. The hydrogen flow of 0.5 g/s is heated up from 0°C to 51°C with a pressure drop of 14 kPa.

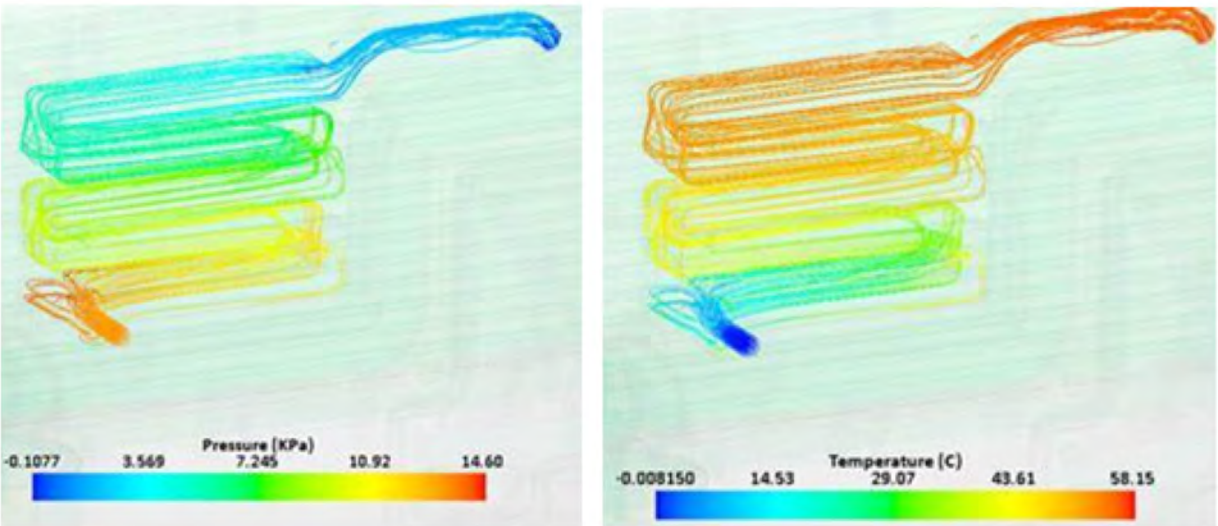


Figure 18: Pressure drop and temperature change in H2 heat exchanger

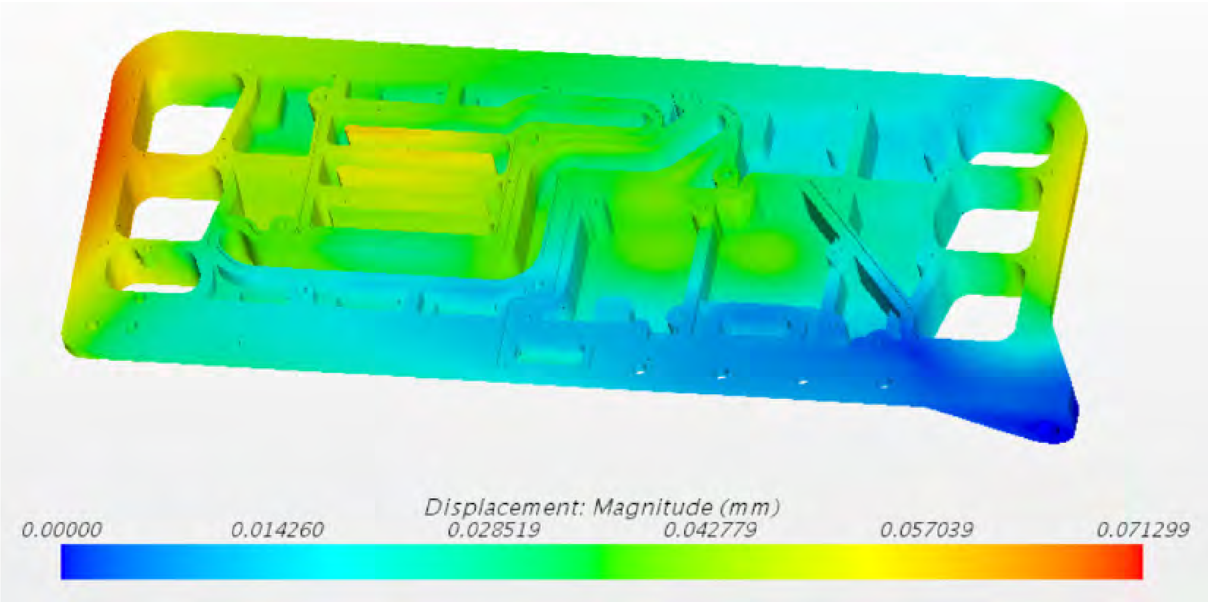


Figure 19: Deformation of front end plate under load

In a further CFD simulation the pressure drop of the cyclone water separator and the temperature distribution along the hydrogen recirculation line have been analysed. Figure 18 shows that the pressure drop in the cyclone occurs mainly on the inlet funnel and the outlet tube, as expected. The temperature of the recirculated hydrogen at the inlet of the ejector is almost 60°C so that at the mixing point with the dry hydrogen which is preheated to 51°C a condensation of water is unlikely.

FEM simulations have been done on the components of the front end of the stack. Figure 19 shows that the structural endplate has been optimised so far that it's deformation under nominal load is only 0.07 mm. This will assure an excellent uniformity of the compression force on the active area

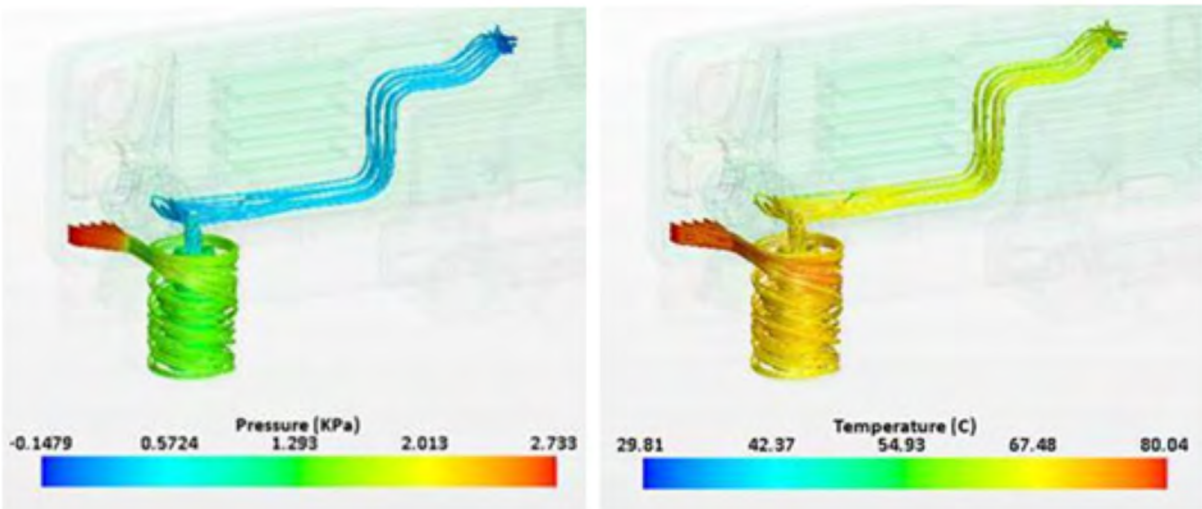


Figure 20: Pressure drop and temperature profile in cyclone water separator

3.3 WP3 FC subsystem prototype realisation

Several sets of component and test interfaces have been built and assembled successfully. Pictures of the prototypes and the outcome of the tests can be seen in chapter 4.5.

Figure 21:Stack with 2 x 48 cells with middle current collector

3.4 WP4 CVM and HSL development

The scope of this WP has been redefined. The development of the CVM has been stopped after completing the initial design phase (illustration of the concept see Figure 22).

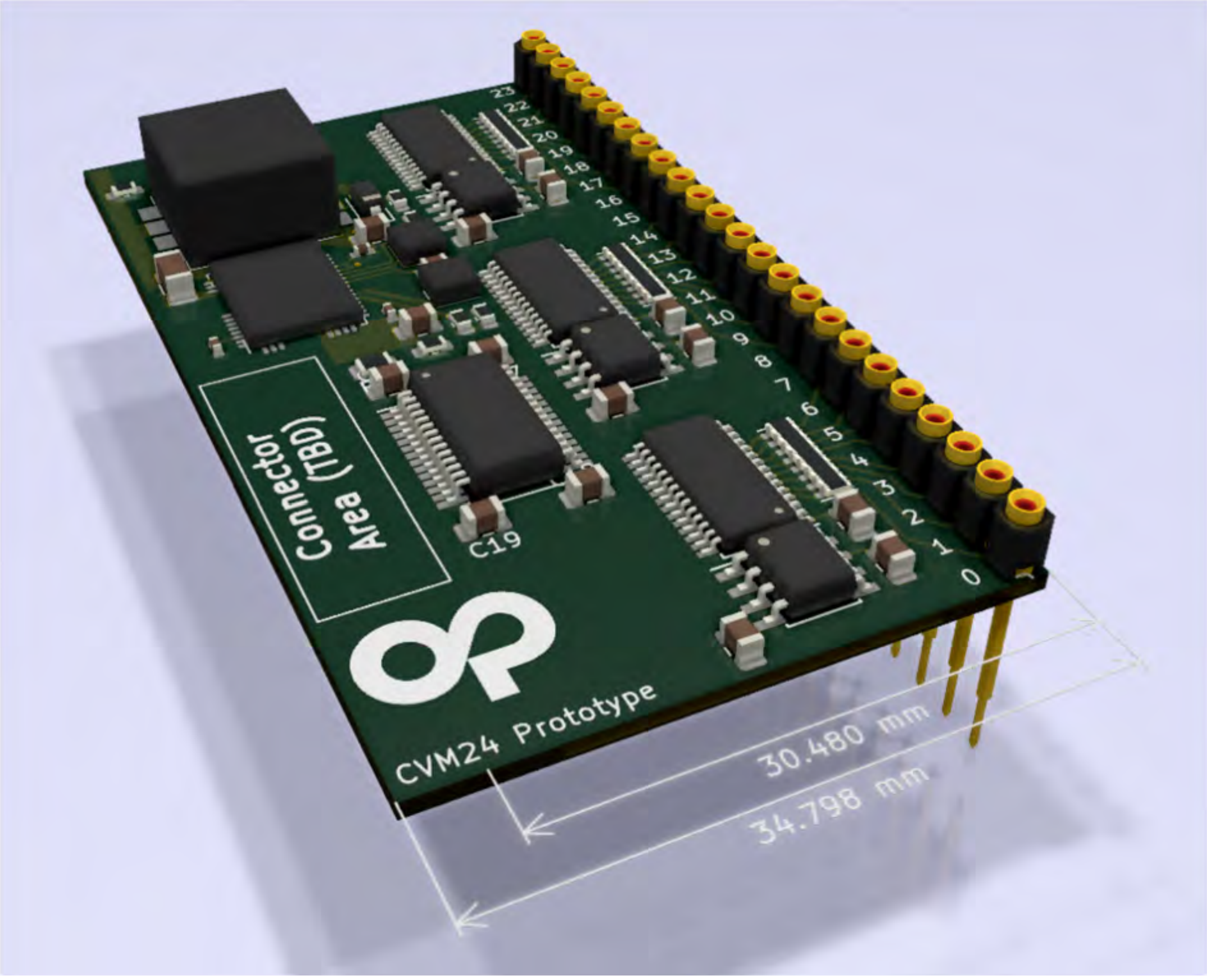
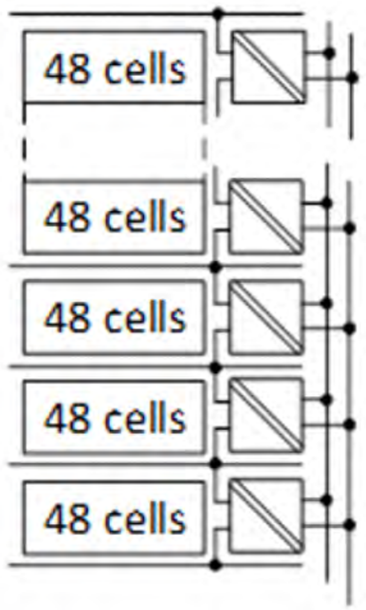


Figure 22: CVM concept with 24 measurement channels

A commercial solution has been found on the market which uses the same technology as we have identified in the design phase so that we have decided to rather test this existing solution than putting ressources into an own development.

The HSL development has been put on hold as it is too closely linked with the final implementation of the system and there is too much uncertainty about the entry market at the moment.

We have therefore put the electronics development ressources into a new project with the HES-SO Fribourg. In a master thesis which was completed until April 2020 a galvanically isolated, modular DC/DC converter was studied. It is scalable to any stack size (multiple of 48 cells) and allows individual current for each block. The schematic is illustrated in Figure 23.



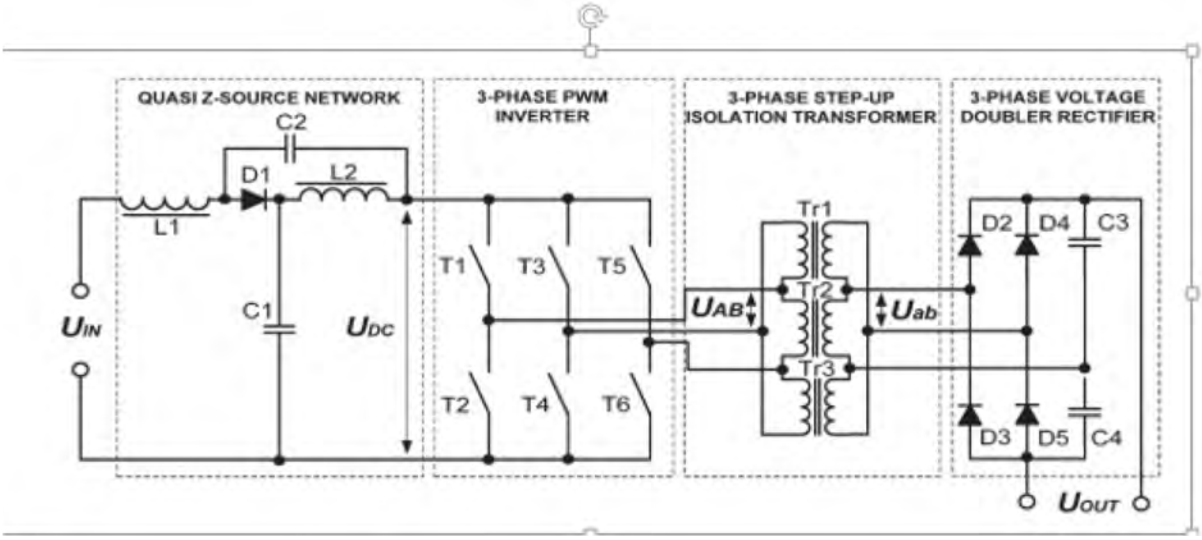


Figure 23: Schematic of concept for modular DC/DC converter

The DC/DC converter shall be directly mounting onto FC stack therefore the design of the current collectors has been changed.

The target efficiency is at least 97% and be cooled with the stack coolant loop at 70°C. The simulations show an efficiency between 96 and 98.2% over the entire power range (see Figure 25).

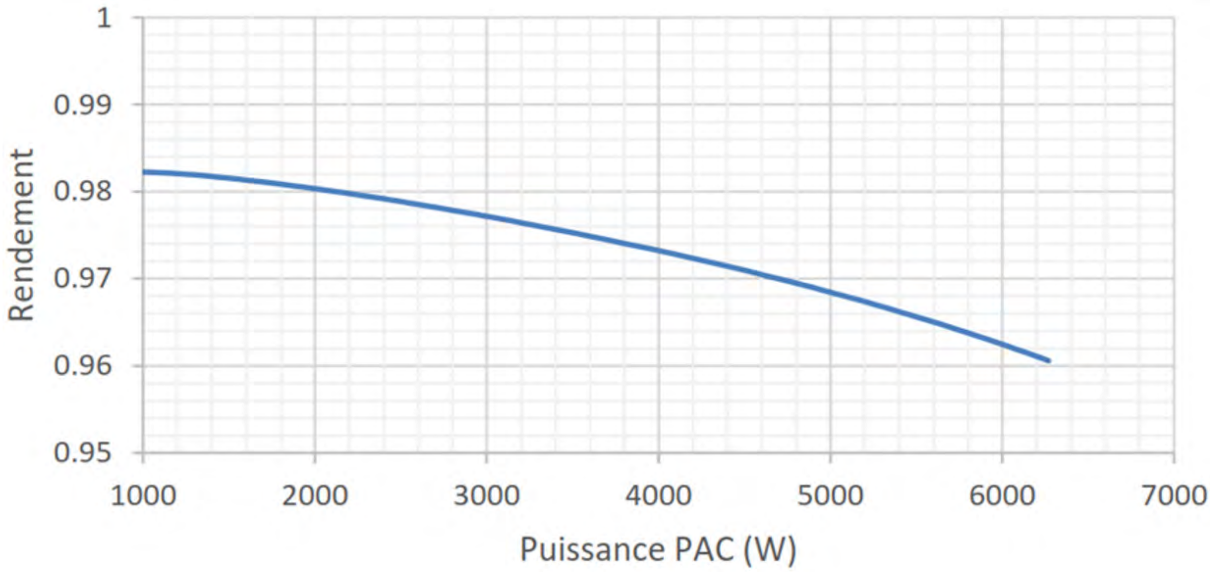


Figure 24: Efficiency curve of DC/DC converter

A low cost design using MOSFET and planar tranformers was investigated. It shall be compatible with very low cell voltage (down to 0.2V in average during freeze start and with negative cell voltage during start/stop.

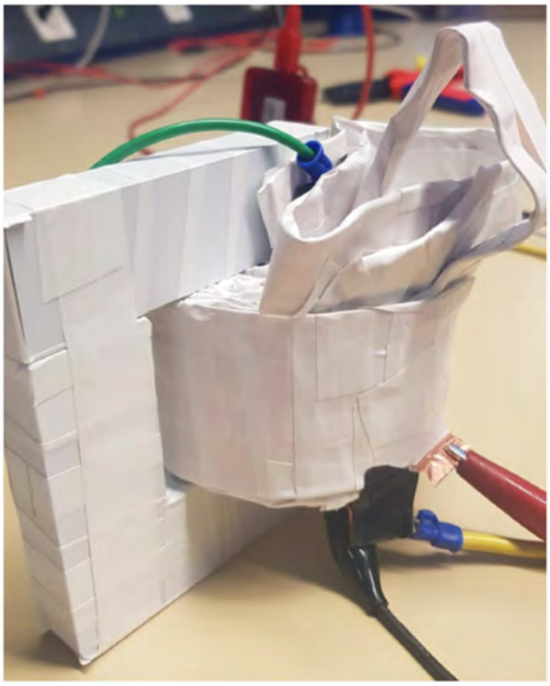


Figure 25: Prototype of transformer

The results of the master thesis are very promising and a further collaboration with HES-SO Fribourg is planned in 2021 to continue the work on the DC/DC converter.

3.5 WP5 Testing

3.5.1 Distribution of compression force

The first tests have been done on the compression hardware. The distribution of pressure in the active area and under seals was measured with a pressure sensitive film. An excellent pressure distribution has been achieved.

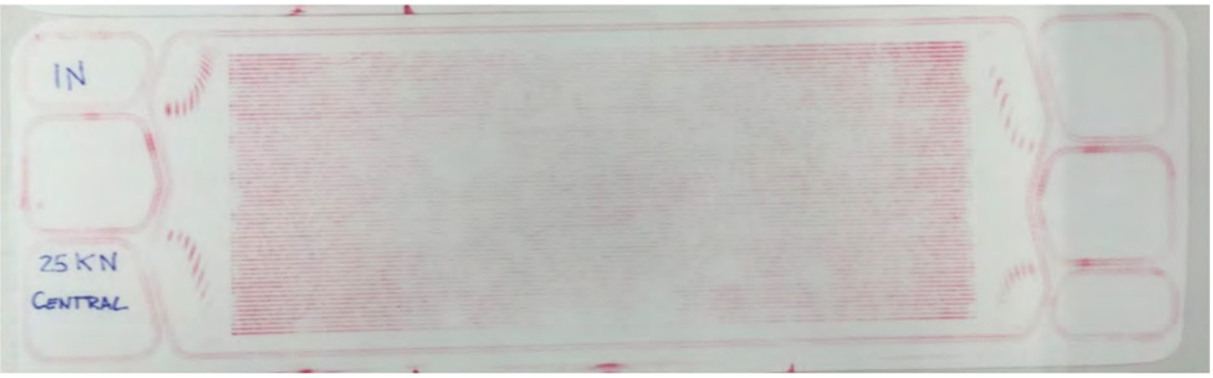


Figure 26: Visualization of compression force with pressure sensitive film

3.5.2 Load cycling of compression hardware

The endplates, side walls, springs and fixing bolts have been tested according to their load cycling capability. An accelerated durability test on a hydraulic compression test stand has prooven 30'000 cycles with 40kN +/-5 kN without any signs of damage. The nominal force is 25 to 30 kN so that this test represents an accelerated life test with a safety factor of at least 1,33.

Figure 27 shows the compression hardware for a 30kW stack mounted on the test bench.

Figure 27: Test bench for load cycling of compression hardware

3.5.3 Short stack testing

Several sets of new MEAs for operation with humid conditions at elevated pressure but also at dry cathode air at ambient pressure have been carried out.

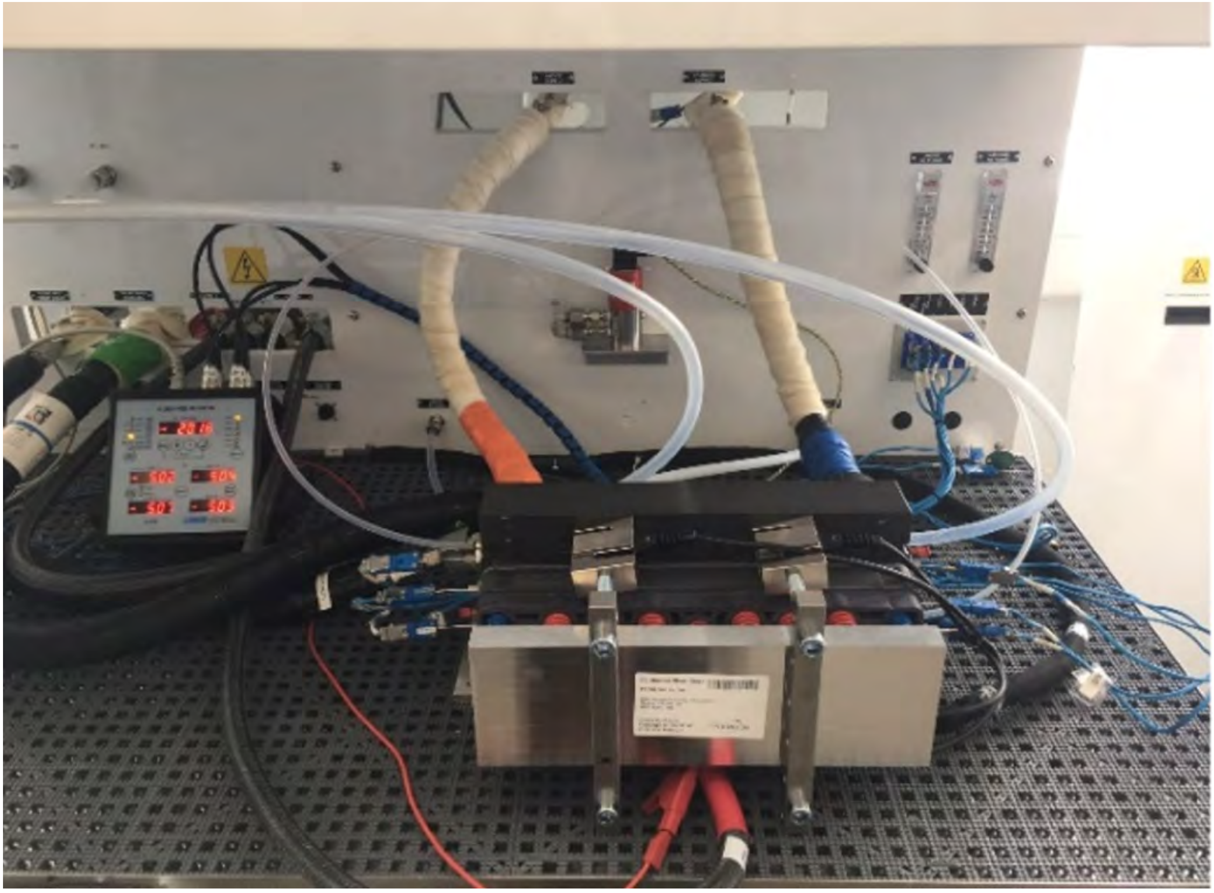


Figure 28: Short stack on stack test bench in Fribourg

A large improvement over previous concept has been found. As illustrated in Figure 29 the problems of lower performance of 1st cell (1) and the instability at 60A (2) have been almost completely resolved.

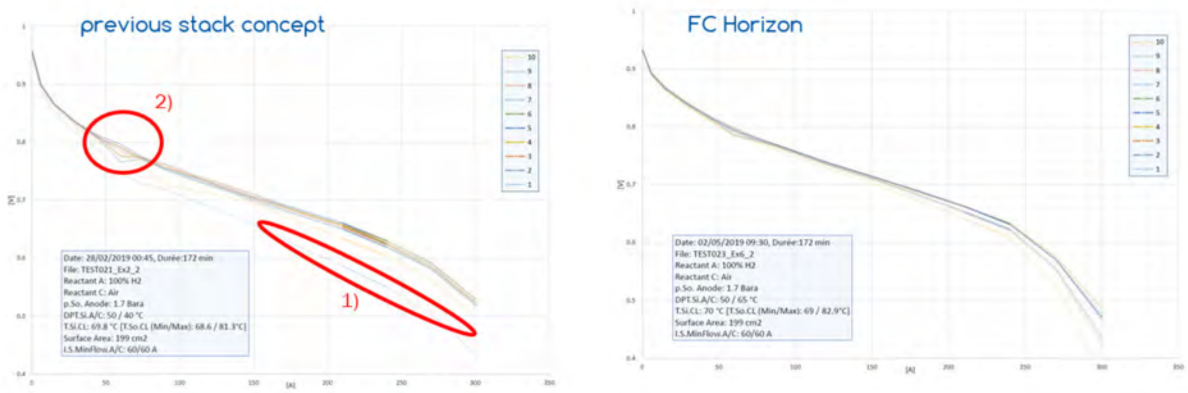


Figure 29: Comparison of polarization curves of individual cells for old and new concept

3.5.4 Temperature distribution on end cell

A special test setup to validate the temperature distribution of the first bipolar plate has been built (see Figure 30). In this setup the front end of the stack can be fed with 70°C coolant and cold, dry hydrogen with flow rates as for 30 kW system. A special compression plate with large openings allows to mesure the temperature profile on the first BPP with a thermographic camera.

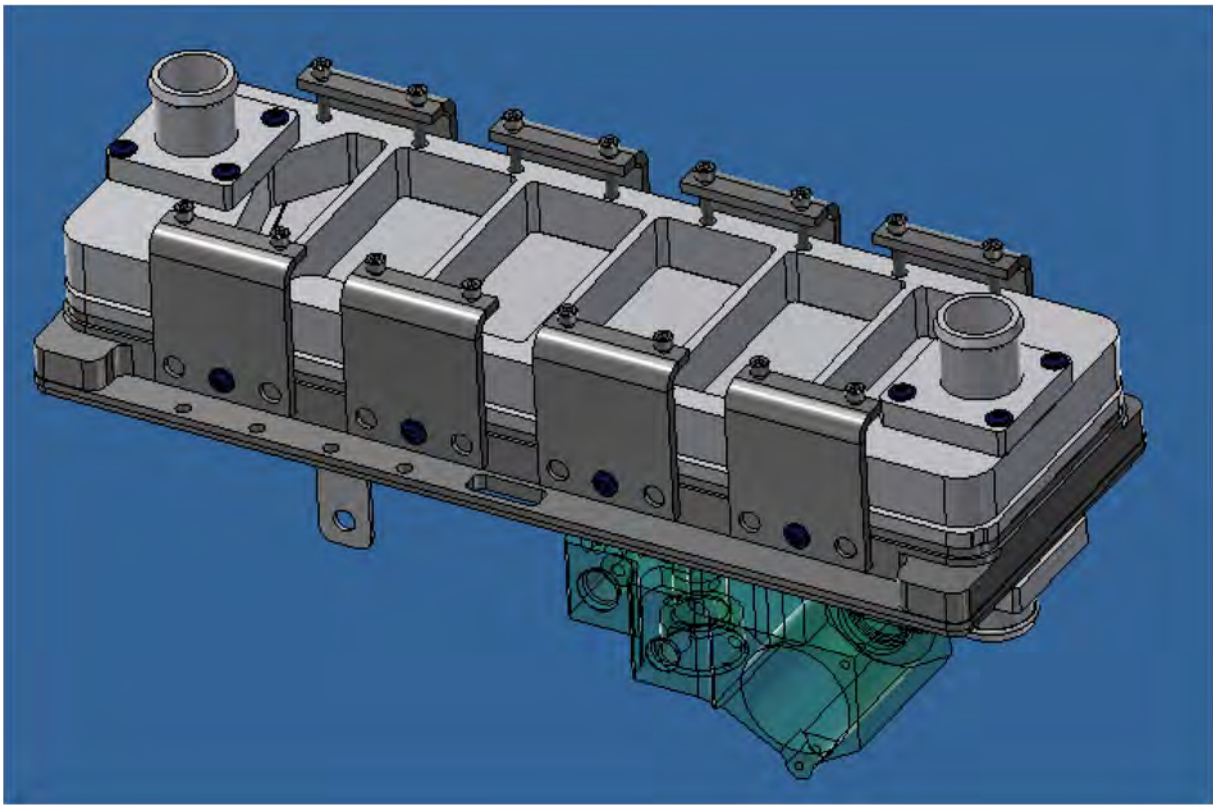


Figure 30:Test setup for thermographic measurement of first BPP

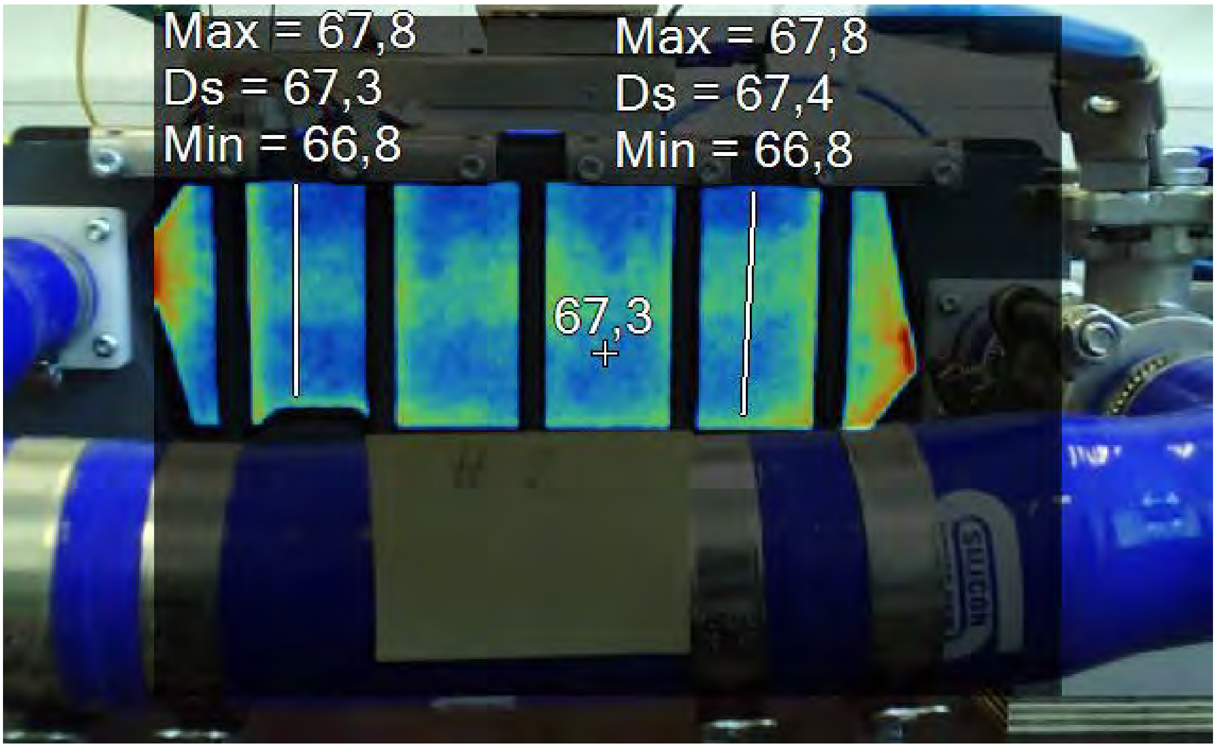


Figure 31: Thermographic image of first bipolar plate shows very uniform temperature distribution

The results are very positive. The concept of integrated H2 heat exchanger has been tested successfully. shows a very uniform temperature distribution, the results of CFD simulations are confirmed.

3.5.5 Anode recirculation with ejectors

A large effort has been done on the testing of the ejectors. It was found out that the commercially available ejectors, which have been used in the previous FC systems, do not have a very good performance at some stack conditions (high humidity and high Nitrogen concentration in the anode flow). An specific ejector design has been carried out and prototypes have been realised with metal and plastic 3D printing.

Figure 32: Commercial ejector (bottom) and newly developed ejector (top)

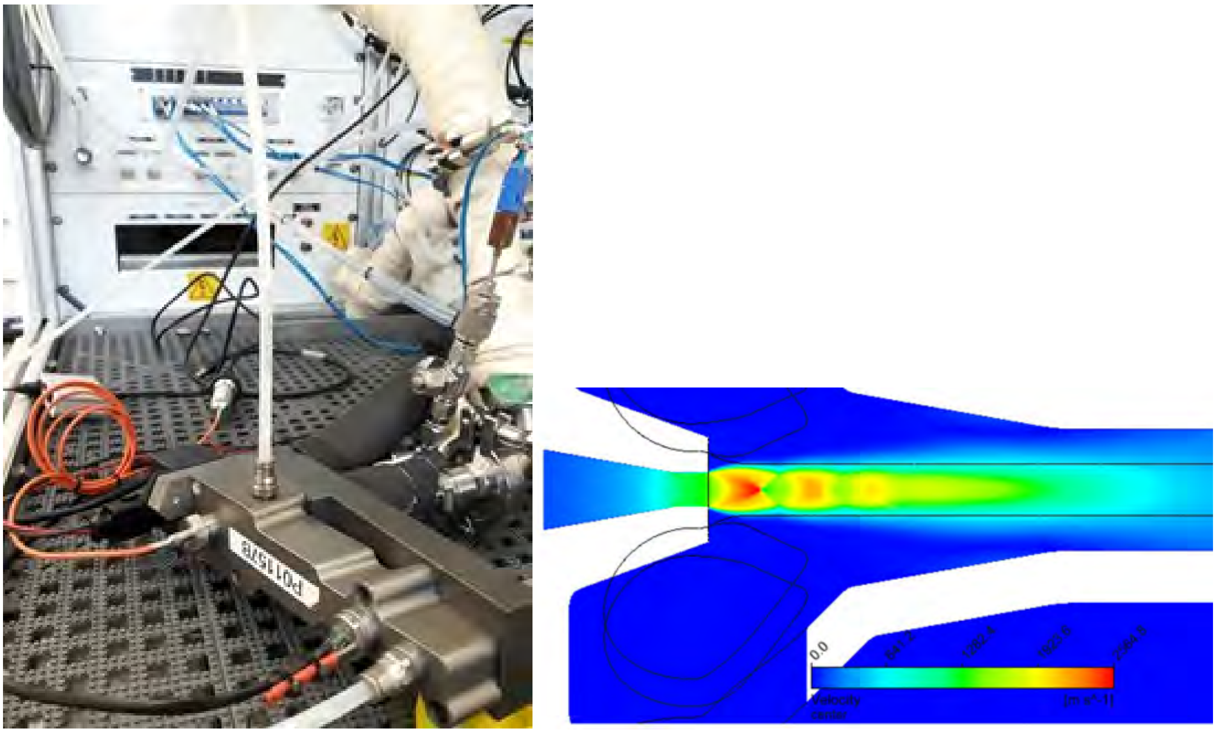


Figure 33: Test setup for ejector / valve combination and CFD simulation of ejector

The achieved results are very good, the performance is significantly improved over the commercially available solutions. Figure 34 shows a comparison of the achievable pressure difference between secondary inlet and outlet of the ejectors. The newly developed ejector builds up significantly more pressure over the entire range of flow and operation pressure.

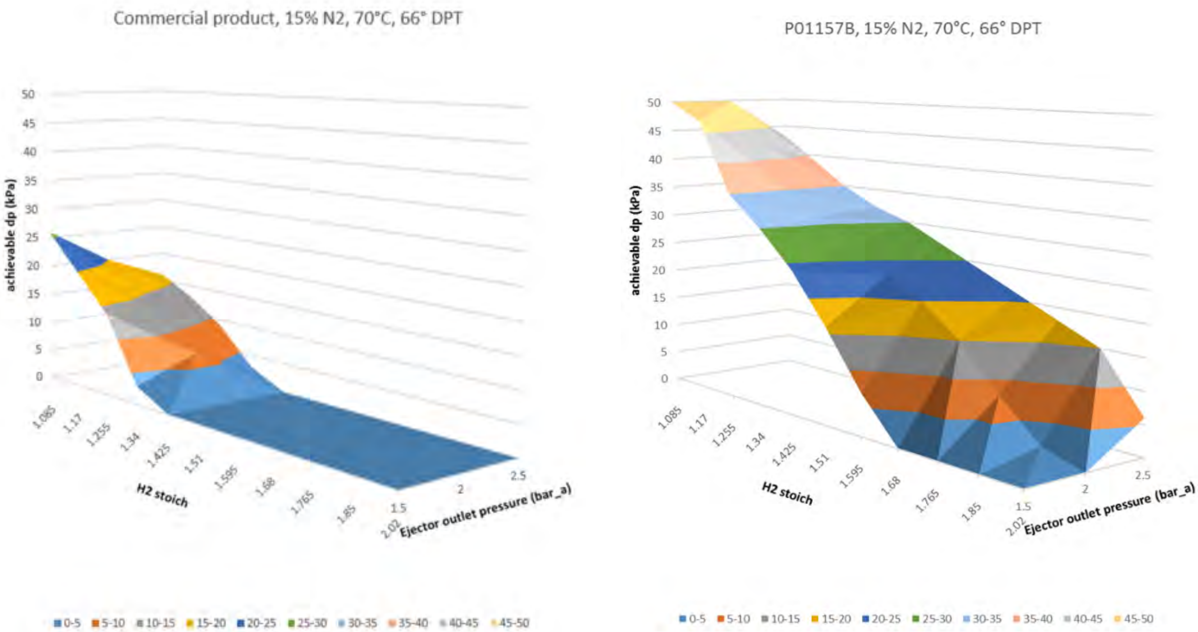


Figure 34: Performance of commercial ejector (left) vs. newly developed ejector (right)

3.5.6 Effectiveness of water separator

In another test setup liquid water in the anode recirculation flow was analysed (see next picture). The interface plate wich integrates the cyclone water separator, the purge/drain valve, the H_2 heat exchanger and the recircuulation path towards the ejector is divided into two pieces: one piece made from Aluminum (green part) and one piece made from transparent polycarbonate. This setup allows to look into the recirculation path to observe water droplets while it maintains the full functionality of the heat exchanger. During the tests described in chapter 4.5.8 it was observed that the cyclone water separator works very well. Even under heavily condensing conditions during heat up phase it was not observed

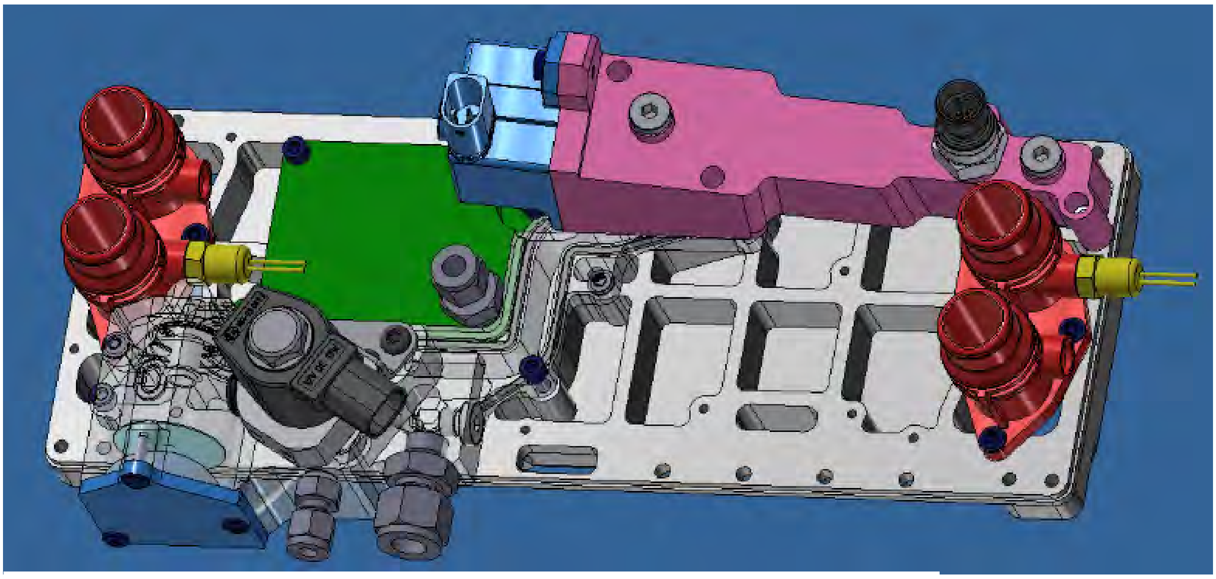


Figure 36: Anode subsytem with transparent part to visualize water droplets in the recirculation loop

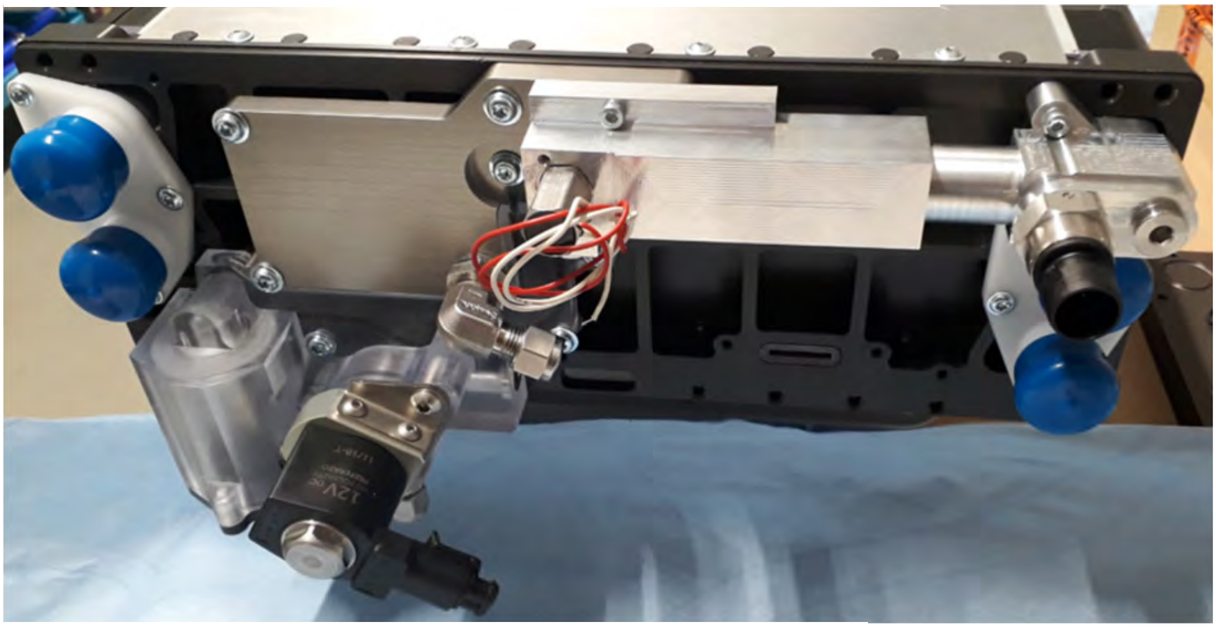


Figure 35: Realization of test hardware

that liquid water enters into the ejector housing. The streamlines of the gas flow in the cyclone became visible with the water droplets moving on the outer cylinder. This is documented in a few videos wich have been sent to the project coordinator.

3.5.7 10kW stack testing

A stack with 92 cells was assembled and characterized on the G500 test stand in Fribourg. This stack has no middle curent collector and was further used on the 10 kW system test (see next chapter). The polarisation curve (Figure 37) shows the same performance as in the short stack testing so there is no negative effects of maldistribution in the manifolds.

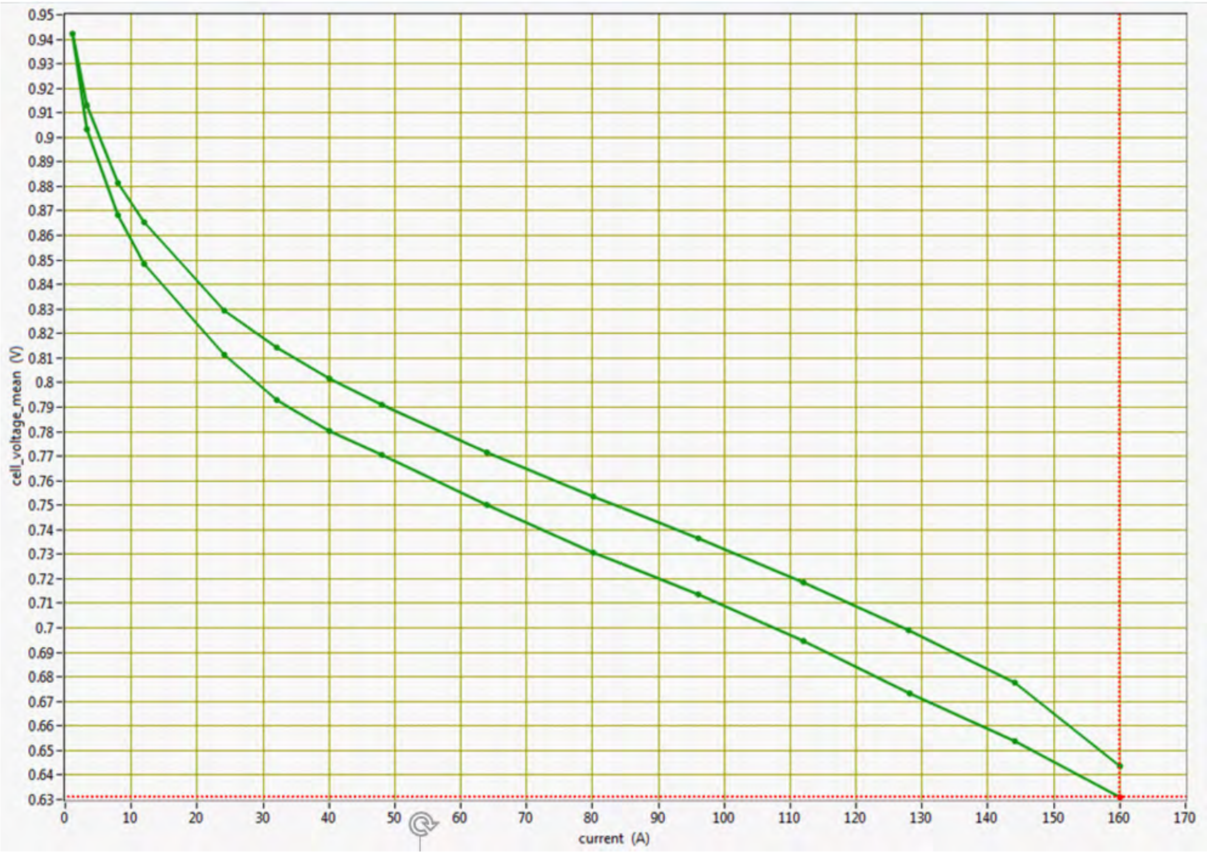


Figure 37: Polarization curve of 92 cell stack

In further tests the operation stability under different temperature, humidity and stoicheometry conditions was tested in order to find out the operation limits. The stack can work with a very low stoicheometry of downt to 1.3 at low power (60Amps) as long as the humidity is not too high (<80% rH). The uniform temperature and compression force distribution has most likely the biggest contribution to this improvement over previous stacks.

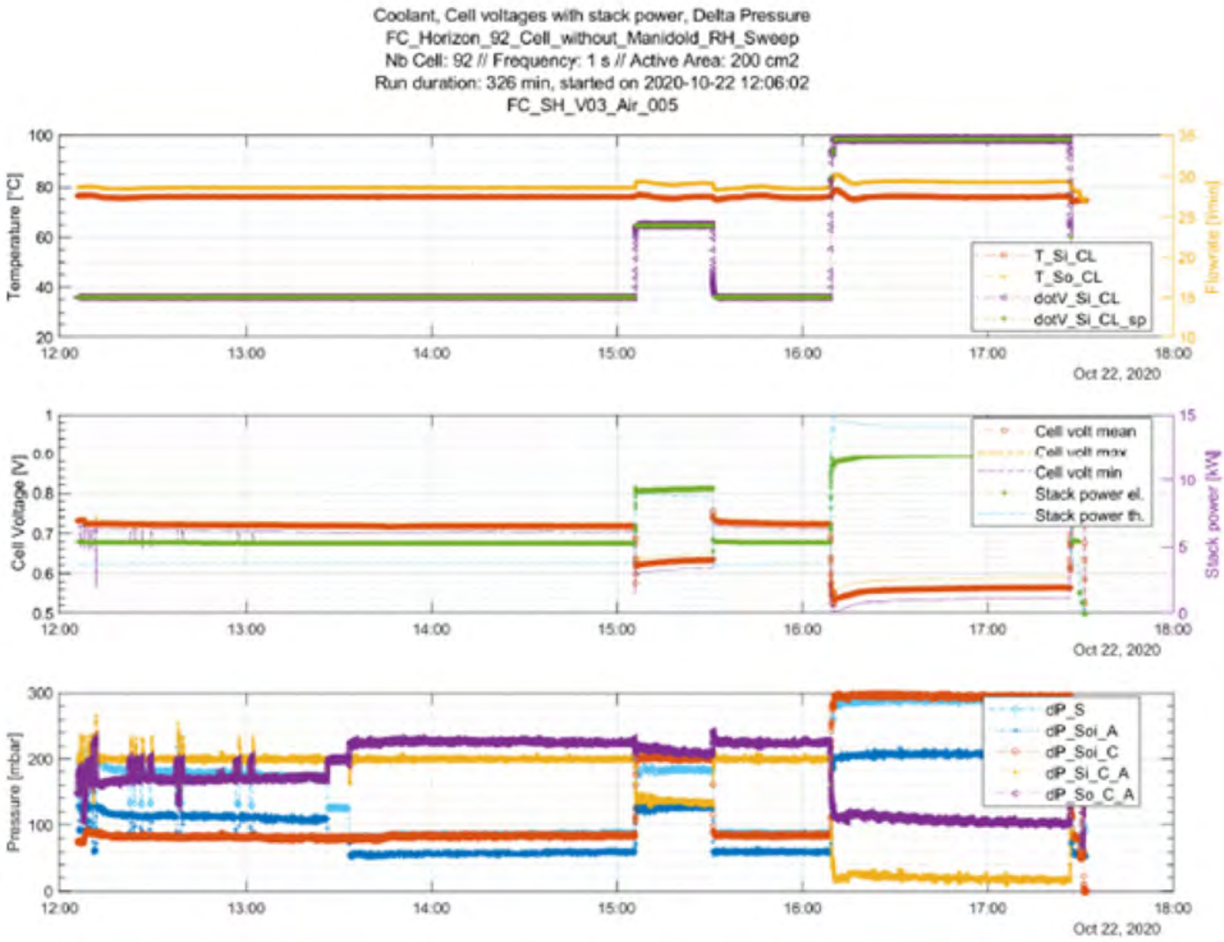
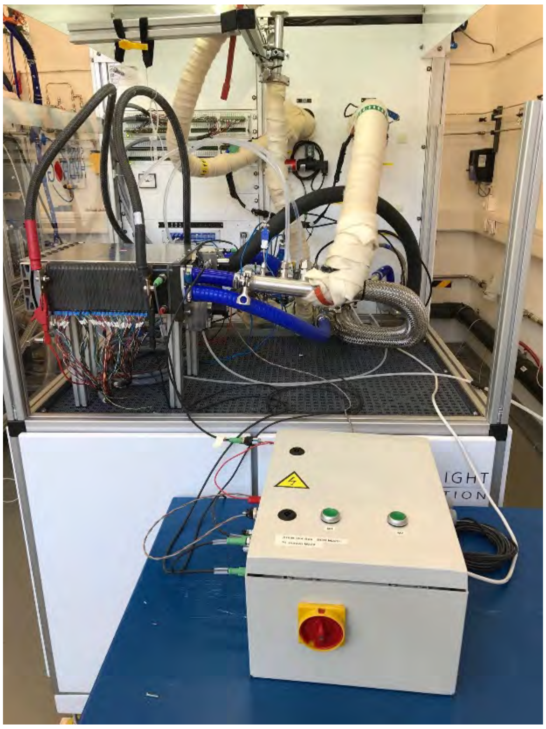


Figure 38:Test of operation stability

3.5.8 10 kW system testing

Finally, the Anode subsystem from 4.5.6 was mounted onto the 92-cell stack and operated in recirculation mode on the G500 test station in Fribourg.



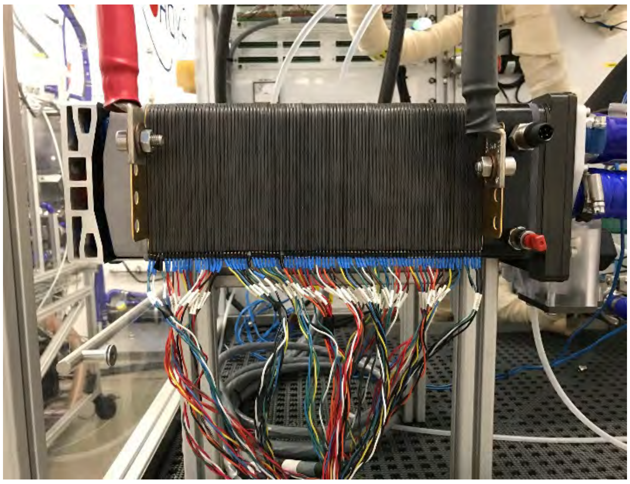


Figure 39: 10kW FC subsystem tested on G500 test stand

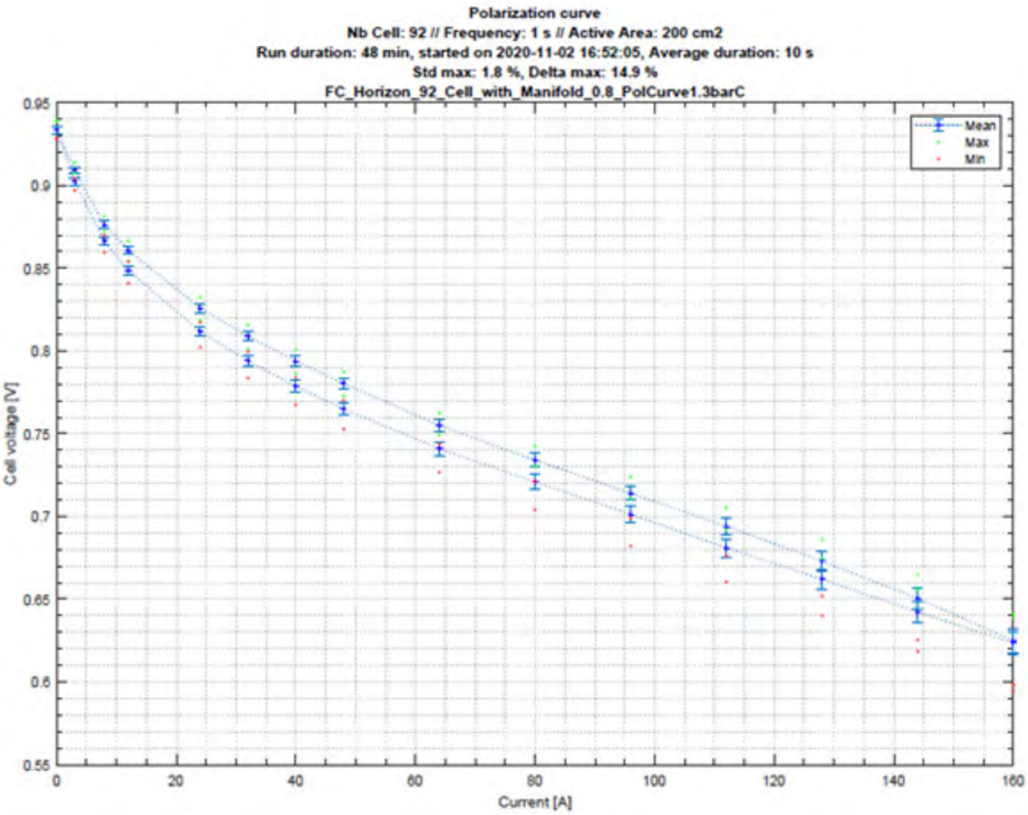


Figure 40: Polarisation curve of 10 kW subsystem

The most important result is the achievable anode stoichiometry in passive recirculation mode (only one ejector with 0.8 mm orifice, no active recirculation pump)

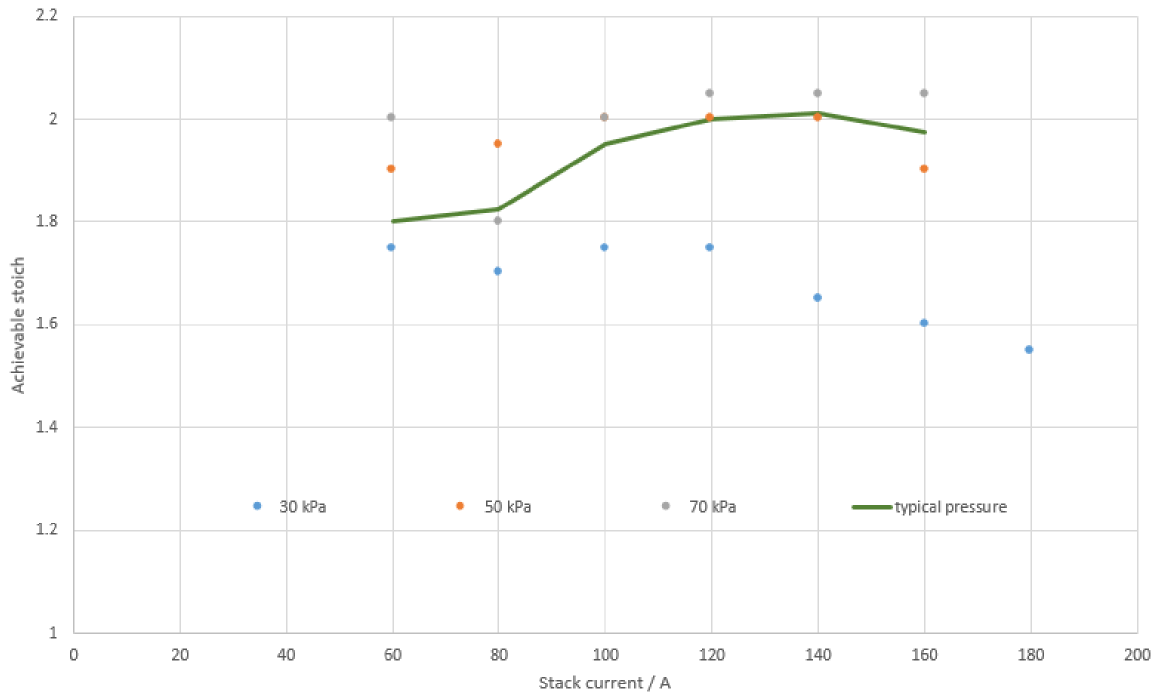


Figure 41: Achievable anode stoicheometry over stack current for different operation pressures

The achieved stoichiometry increases with higher system pressure especially at high current density. This correlates well with the typical stack operation pressure curve so that a stoichiometry between 1.8 and 2 can be reached over a very large operation window.

3.5.9 Cathode blower testing

The existing test bench for air subsystem components has been renovated (more precise flowmeter, modular controller). Blowers from Micronel have been installed and a durability test has been started.

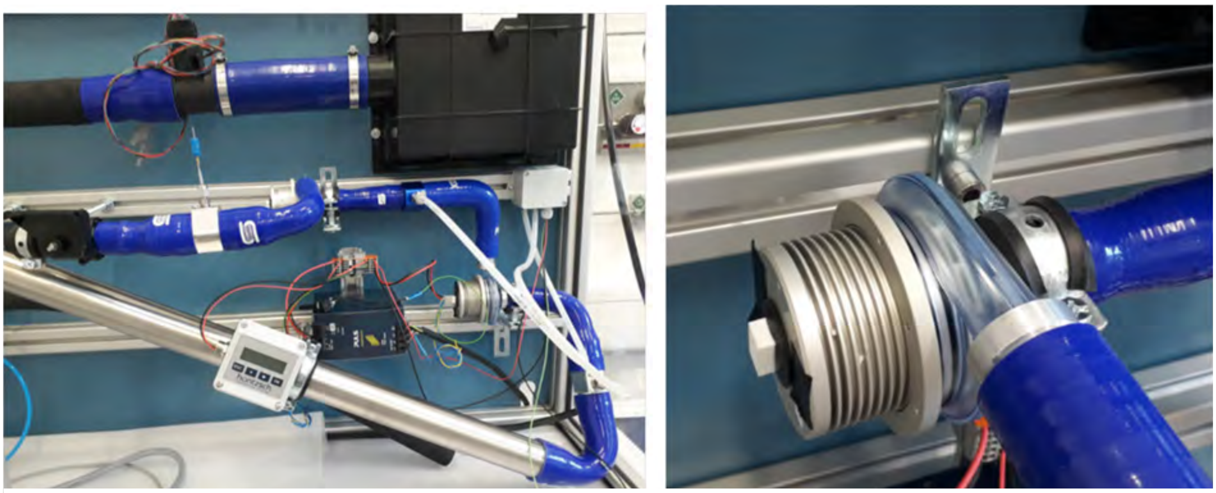


Figure 42: Blower from Micronel in air subsystem test bench

It is necessary to put two blowers in series to overcome the pressure losses of the cathode flowfield at full load. The supplier of the blowers has proven a lifetime of 15.000 hours in single stage usage recommends to validate the lifetime in two stage configuration as the downstream blower is exposed to higher pressure and temperature. This testing has been stopped since at the momemnt we don’t see any application for a low pressure system.

3.5.10 Humidifier testing

Instead of testing off-the-shelf humidifiers it was decided to lauch a in-house development of humidifiers based on a membrane from Fumatech. A design of the menbrane for humidifiers for FC systems from 10 to 30 kW has been worked out together with Fumatech, the water transfer and pressure drop has been simulated and 100 samples of the membrane have been produced. 66 of them are assembled in a housing which is integrated into the rear end of the fuel cell stack. It turned out that the assembly was very difficult and that it was impossible to achive a sufficient gas tightness between the dry and the humid flow, because the membranes were not flat enogh. Even when they were devided into subassemblies of only 10 membranes and seperated with a rigid separator it was not possible to achive sufficient results.

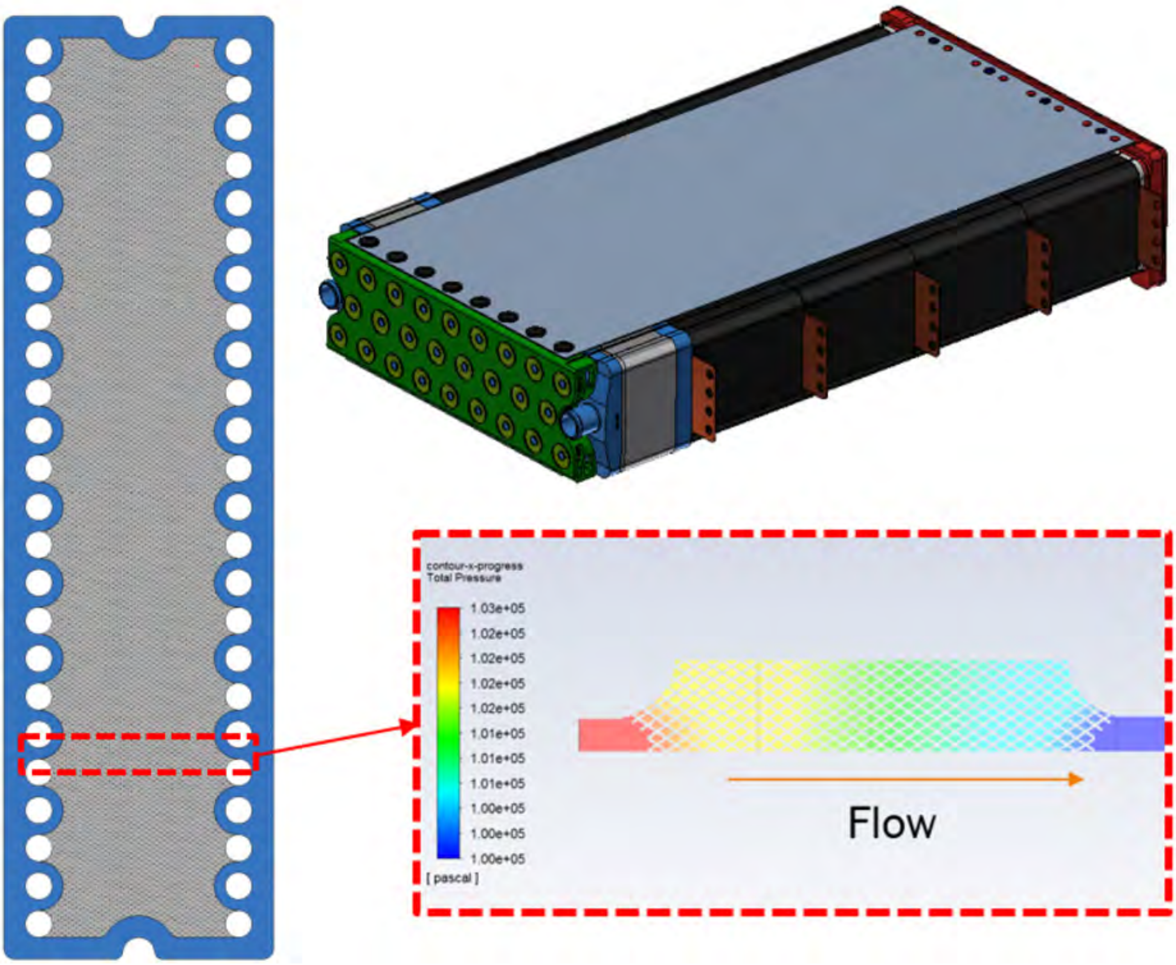


Figure 43: Membrane humidifier for integration into FC stack

It was further tested in a compression block how high the compression force has to be in order to avoid

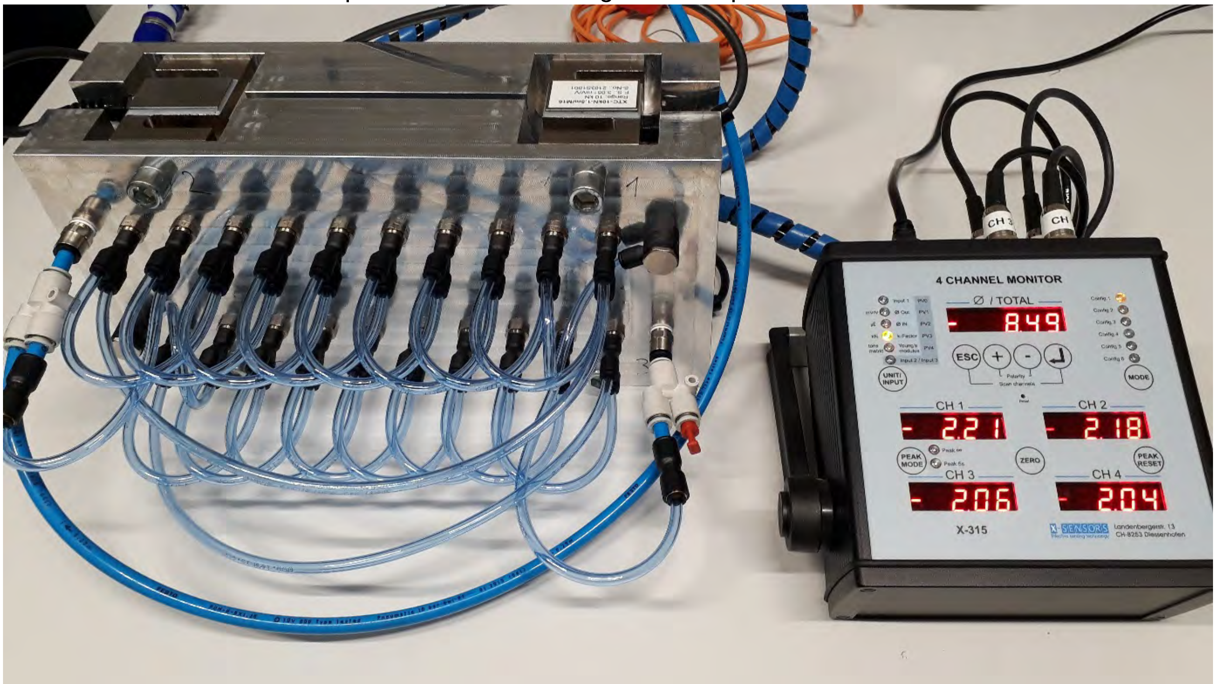


Figure 44: Measurement of gas leakage and pressure drop under variation of compression force

internal leaks. The force was much higher as expected and under this force the pressure drop from inlet to outlet was much to high for a fuel cell application. The concept of overmolding a mesh together with the membrane with an elastomer has to be reworked.

3.5.11 Sensor testing

In previous systems standard automotive temperature sensors were used (e.g Bosch part nr. 0 281 002 209). In such sensors the sensing element (a NTC) is mounted in a relatively thick and heavy brass housing so that the thermal inertia is relatively high. For the thermal management of a fuel cell system it is very important to follow strictly the recommended operation temperature window, even in transient conditions. A new temperature sensor with reduced thermal inertia was developed and compared to other industrial sensors and also to thermocuples, wich have the lowest possible inertia.

The response time could be improved from 13s to 2s.This is considered to be fast enough.

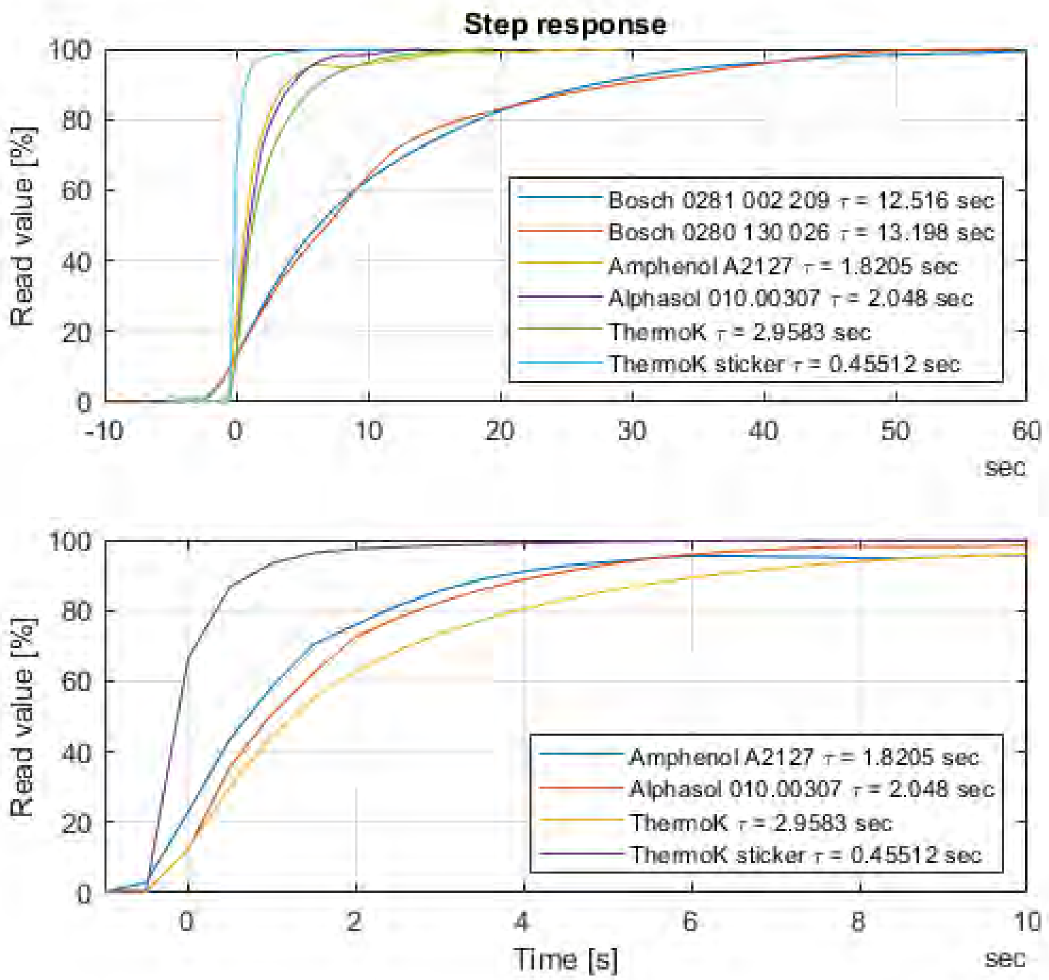


Figure 45: Step response of different temperaure sensors

4 Conclusions

Most of the project goals have been achieved successfully. A significant improvement of the temperature distribution and the uniformity of compression force could have been realized and demonstrated with test results. As a result the cell voltage of the first cell, which was often 30 to 50 mV below the average could be increased close to the average cell voltage. This should reduce the risk of premature aging of this cell. Load cycling tests of the stack compression components have been completed successfully.

The recirculation and preheating of H2 has been well improved and allows stable operation under all relevant operation conditions. New concepts such as the integrated humidifier and the in-house designed ejectors have been added to the project. The ejector design was optimized in several steps by CFD simulations and validated in intensive testing on component and subsystem level. The membrane which was chosen for the integrated humidifier has to be further improved.

The development focus on the electronics have been shifted from CVM and HSL to a new modularly DC/DC converter design. Final tests of the 10 kW stack and the entire 10kW subsystem have been completed in autumn 2020 and show good results. Additional components such as Sensors and blowers have been tested.

5 Outlook and next steps

The new concepts and designs which have been developed in this project will be used in future developments. The compression concept, the end plate design with integrated cyclone and H2 preheating as well as the additional coolant flow field in the isolation plate will also be used on a new in-house FC stack development which has been started in 2020. This might be the subject of a follow-up project.

Due to the new constellation with the joint venture that Plastic Omnium is about to create together with ElringKlinger there is also the opportunity to implement and further elaborate these designs in the NM5 and NM12 stacks of ElringKlinger. The stacks will be used in Plastic Omniums FC systems in the upcoming years and it is a clear target for Plastic Omnium to deliver FC systems to automotive customers in large numbers. Media modules for these stacks are already being developed by EK but they only consist of water separators, drain/purge valves and some sensors. The ejectors, their combination with proportional valves, the preheating of Hydrogen and the concepts to achieve a uniform temperature distribution in the endplate can be adapted and further improved.

The concept for the integrated humidifier can be adapted to the footprint of the EK stacks. More work will be required on the design of the flow-field layer and on the seal to find a compromise between sealing force and pressure drop.

The air compressor remains to be the most important BOP component for the fuel cell system. For 30kW systems only very few components have been developed so far any they all have major drawbacks such as low efficiency, unsuitable pressure / flow curve and high price so it is will be necessary to further develop a suitable component for the 30 kW project. The Swiss companies Celeroton and Fischer are good candidates for such a development.

As EK stacks require a CVM with single cell voltage measurement we will also analyze if the concept which has been developed within this project can be used.

The DC/DC converter project shall be continued in a new master thesis with the HES-SO Fribourg. The concept works also with EK stacks.

6 National and international cooperation

Common usage of facilities and exchange of technical expertise with PSI, Villigen

Key suppliers from Switzerland

- Peter Mechanik (Holderbank) and von Allmen (Pfäffikon): Machining of parts
- CSEM (Neuchatel), Ecoparts (Hinwil) and Prodartis (Appenzell): 3D printing of functional parts
- Micronel: Cathode blower

Key suppliers international

- Nisshinbo (Japan): Bipolar plates
- (Freudenberg (Germany): Seals on bipolar plates
- Greenerity (Germany): MEA
- IRD Fuel Cells (Danmark): MEA and
- Fumatech (Germany)