32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Improving Fuel Cell System Robustness with Ion Exchange Technology

Simon Leininger, Andreas Wildermuth

MANN+HUMMEL GmbH, Schwieberdinger Str. 126, 71636 Ludwigsburg, Germany, simon.leininger@mann-hummel.com (corresponding author)

Summary

Fuel cells will play an important role in reducing CO_2 emissions from transport, especially for HD use cases [1]. As the LT PEM technology has reached technical maturity, significant system cost reductions must be achieved to achieve customer acceptance without sacrificing durability and robustness. Current fuel cell systems have an overall efficiency of ~ 50 %. The remaining 50 % of energy lead to heat generation, which must be removed by the coolant loop at very high flow rate. In order to ensure a robust running system and avoid electric shorts, the electrical conductivity in the fuel cell stack has to be kept low. By using the ion exchange technology, ions which are released by several components in the coolant loop, are separated. In addition to highly-efficient ion removal, low pressure drop, mechanical robustness and costs are the challenges in the development of such ion exchangers.

Keywords: fuel cell, cooling, reliability, cost

1 Motivation

Climate change is one of the major threats to mankind. To reach the target of maximum 1.5 °C temperature rise compared set by the COP21 Conference in Paris [2], emissions from transport, accounting for 23 % of the total CO_2 emissions [3], have to be drastically reduced. Whereas Li ion batteries are limited in power density and capacity, FCEV offer driving ranges and fueling comparable to today´s ICE vehicles.

To remove the heat generated by the fuel cell stack, liquid cooling with water-glycol mixes is often used. It is crucial to keep the liquid at a very low conductivity to avoid electrical shorts in the fuel cell stack. During operation, ions enter the liquid, e. g. from metal surfaces of coolant loop components, additives from plastics, and corrosion [4], and the conductivity increases. To keep the conductivity low (typically < 5 µS/cm) and to protect the coolant loop from accelerated corrosion, ion exchange technology is applied.

MANN+HUMMEL has already developed the I2M PROTECT+ion Omniflow ion exchanger [5], which is available as off-the-shelf product in 4 different sizes. What sets it apart from conventional ion exchangers is the fact that a patented lattice structure is used to fix the resin bed. This product has been developed for mainly stationary fuel cell applications. Now, MANN+HUMMEL has developed a new ion exchange design for automotive fuel cell application.

Lowering system cost and degradation are essential for the market success of LT PEM Fuel Cell technology [6]. The following chapters will highlight how this can be achieved in case of the ion exchanger for the fuel cell coolant circuit.

2 Design

Today, most ion exchangers are operated in stationary applications, mostly for water treatment. Developing a new ion exchanger design for mobile fuel cell application requires adaptions and changes in traditional design guidelines. The following aspects are especially crucial:

- **Packaging restrictions:** In order to fulfil packaging restrictions a high capacity resin has to be selected and the design has to be optimized.
- **High flow-rate:** The maximum flow rate in the coolant loop can vary in a range of ~7,000 to 15,000 l/h, which would result in very high pressure drop in the ion exchanger. For low superficial velocities viscous forces are dominant, whereas for high velocities inertial forces are getting more dominant (see Eq. 1). To avoid high pressure losses and, as a result, the destruction of the resin the flow rate in the ion exchanger must be minimized. Generally, there are two options, the ion exchanger can be either installed in a bypass or a bypass can be included inside the ion exchanger housing, i. e. in both cases only a certain ratio of the total flow rate is passing the ion exchanger itself. As the contamination level and the total amount of coolant are low both design approaches are reasonable. To avoid high pressure losses in the system, the flow rate through the ion exchanger should be as low as possible and as high as necessary.

$$\Delta p = \frac{150\mu L}{D_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^3}v_s + \frac{1.75\rho L}{D_p}\frac{(1-\varepsilon)}{\varepsilon^3}v_s|v_s| \qquad (1)$$

- **Low ion contamination level in the system:** In standard water treatment applications the ion concentration at the inlet is significantly higher compared to the outlet. Therefore, the ion exchanger will be loaded from one end to the other until a breakthrough occurs, i. e. the resin has to be regenerated or replaced. For fuel cell application, the difference between inlet and outlet ion concentration is relatively low. Here, it has to be considered that the effective capacity depends on the inlet concentration, which can be more significant than the establishment of a sharp loading profile as depicted in Fig. 1.

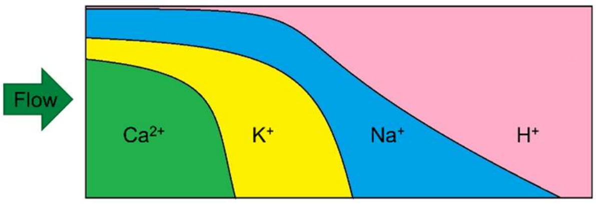

Figure 1: Loading profile of ion exchanger

Furthermore, the ion exchanger should be able to cope with a broad temperature range (-40 – 100 °C) and different vibration profiles, which can occur during operation. Special attention should be paid to the resin. Low temperatures could lead to a breakage of the resin, whereas high temperatures could lead to the loss of functional groups resulting in lower capacity. High mechanical stress could lead to abrasion or even disruption of the resin beads. In addition, an intensive demixing of anion and cation resin can affect the ion exchanger performance. For all these conditions the robustness of the ion exchanger has to be given.

2.1 Description of Design

The developed ion exchanger is an openable system with a replaceable cartridge inside. During the service, only the cartridge is replaced, not the complete housing. It consists of a plastic housing, a cover and a screwing ring and the internal cartridge with the resin. The adaption of the ion exchanger to the inlet and outlet hoses is effected by standard DIN 3021-A-26 studs and the corresponding clamps. The studs are axially orientated to minimize the pressure drop inside. The ion exchanger can be placed in the bypass flow as well as in the full flow of the coolant circuit. Assembled in the full flow, an internal bypass within the ion exchanger housing can be realized.

The bracket for the installation into the vehicle is directly molded to the housing, so that no additional bracket is necessary. Integrated bushings take over the force of the bracket screws.

The inner cartridge contains the ion exchange resin and is axially flushed by the coolant with a maximum opening inlet and outlet area for a homogeneous flow throughout the cartridge. It is self-centering into the housing and provides an integrated sealing towards the housing for the inner tightness. To keep the resin inside, the cartridge provides overmolded 70 µm stainless steel meshes on the inlet and outlet side.

The used material of the housing as well as for the inner cartridge is a low ion discharging PP-GF30. The housing is designed to fulfil typical automotive customer requirements regarding static and dynamic pressure (3 bar max. operating pressure) and vibration. Fig. 2 shows this ion exchanger from the outside.

Figure 2: Ion exchanger for fuel cell application

Fig. 3 shows a section cut of the ion exchanger. With an ion exchange capacity of 705 meq (anion + cation total capacity), the IEX provides a maximum usage of the given space inside the housing. This ensures a minimum need of package space in the vehicle.

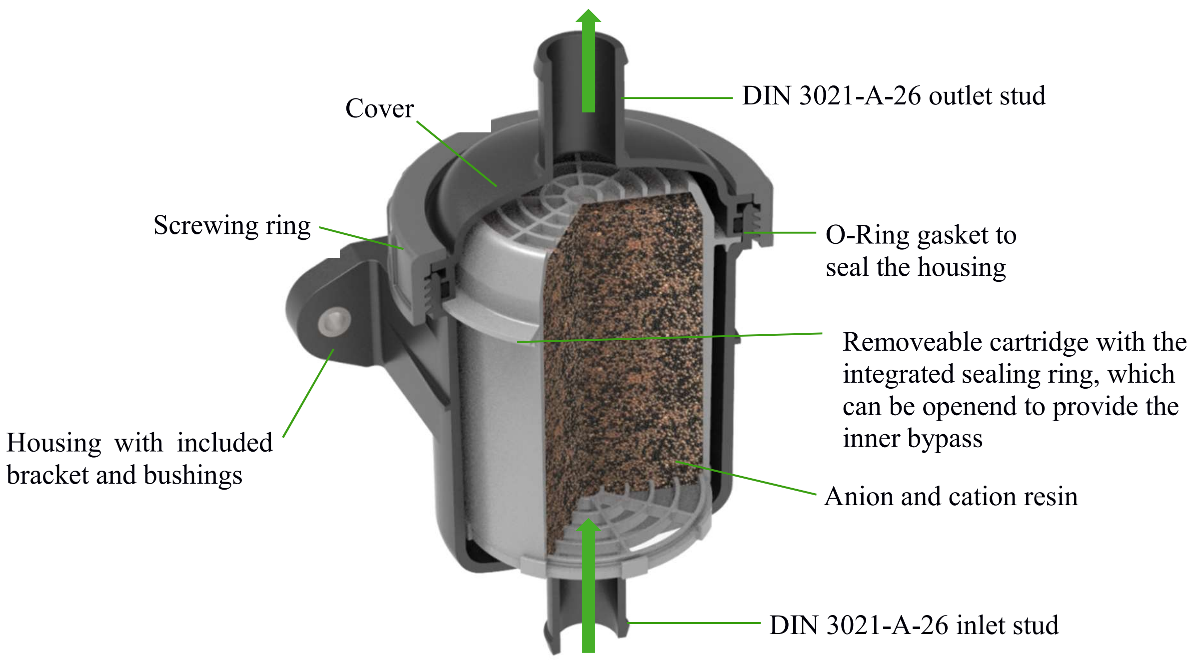

Figure 3: Section cut of the ion exchanger

2.2 Serviceability

For the service, the screwing ring of the ion exchanger can easily be opened and as it is loose on the cover the hose needs not to be disassembled from the cover. It was also taken care that only a small volume of coolant runs out during the opening. Subsequently, the old cartridge can be taken out and the new one is placed into the housing. Last step is the closing of the screwing ring. Changing only the cartridge makes the service easy and ensures a low waste of plastic material.

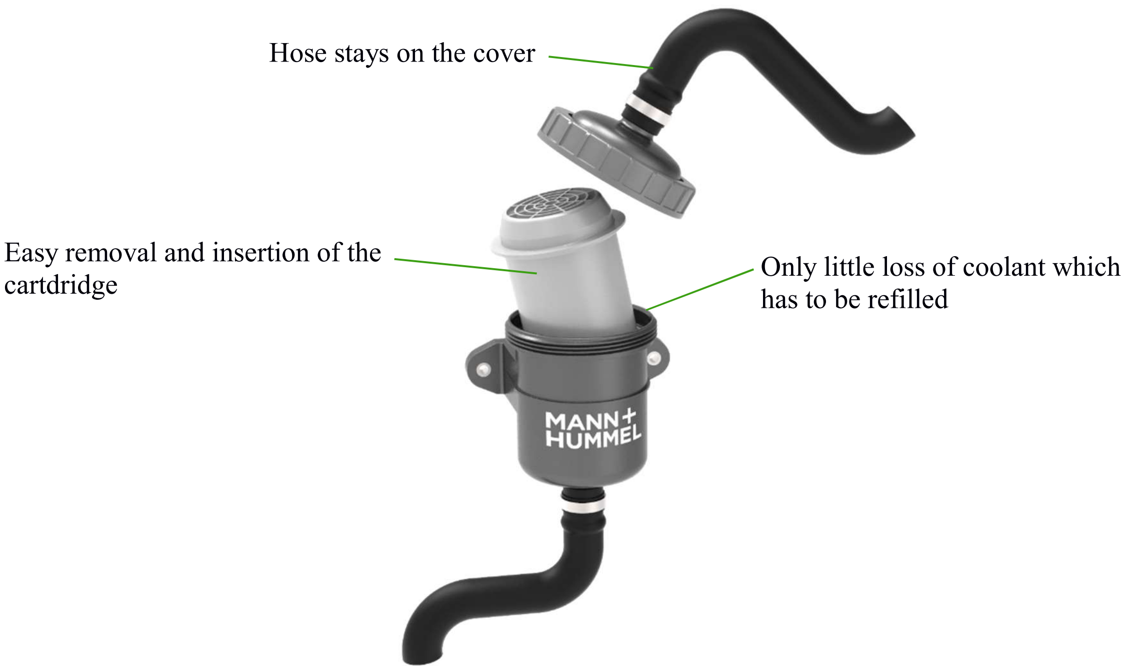

Figure 4: Ion exchanger during service

2.3 Ion Exchange Resin

The resin used for this application is a 1-to-1 equivalent ratio of a strong basic anion and strong acid cation resin in the OH- and H+ form, respectively. The resin beads are monodisperse with PS-DVB copolymer as the basis for sulfonic acid and quaternary amino functional groups. These resins can be applied to any application, which demands the highest effluent purity, highest operating capacity and longest resin life. The resin has to be kept moist during the production process and life time of the product to ensure the quality of the resin.

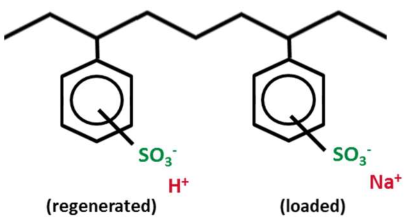

Figure 5: Strong acid cation exchanger (SAC) with sulfonic acid group

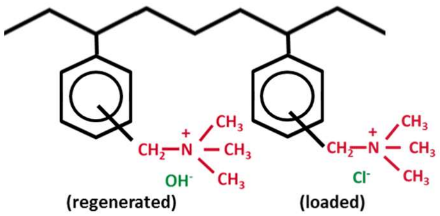

Figure 6: Strong basic anion (SBA) exchanger with quaternary amino group

2.4 Materials

Special attention should be paid to the used materials in the coolant system. In addition to chemical resistance against water glycol mixes at temperatures of -40 – 100 °C the discharge of chemical components affecting the el. conductivity of the fluid should be considered. Therefore, a screening of potentially applicable materials was done. Tension rods of the respective material were stored in ultrapure water with a defined sample surface / fluid volume ratio at 105 °C for 1008 h.

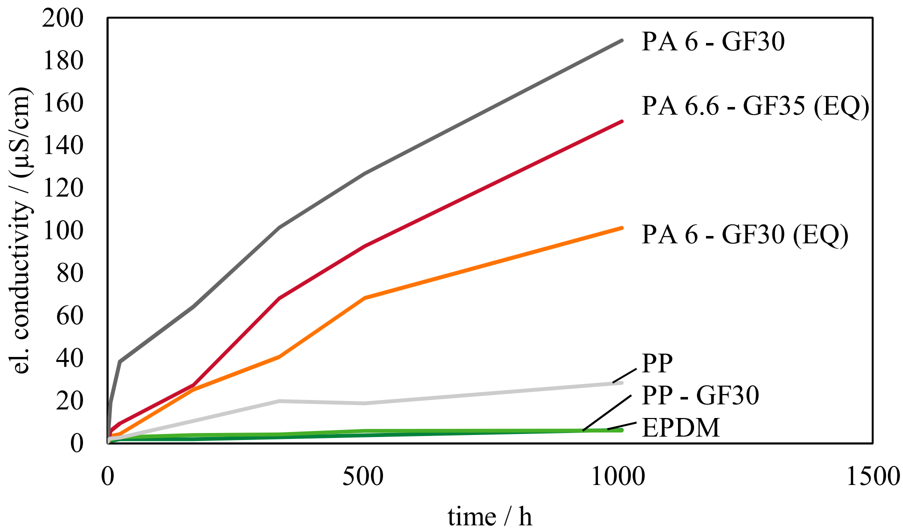

Figure 7: Change in el. conductivity after storage

In Fig. 7 the change in el. conductivity after storage can be seen for representative materials. For this screening, standard PP and PA materials were selected as well as optimized materials for electrical components (EQ). PA 6 - GF30 is showing a continuous increase resulting in an el. conductivity of > 180 µS/cm after 1008 h, but even the optimized PA materials show a significant increase in el. conductivity. Generally, PP materials are showing a lower ion discharge compared to PA materials. In case of PP - GF30 and EPDM, there was no significant increase in el. conductivity detected. It has to be mentioned that the results can differ between different compounds of the same base material. Therefore, it is recommended to do such storage tests of the respective compound. MANN+HUMMEL is using for the ion exchanger housing and cartridge the shown PP - GF30 material and an EPDM O-ring.

2.5 Manufacturing

The key competence in the production of ion exchangers is the filling process of the cartridge. It has to be ensured that the correct ratio of anion and cation resin is filled into the cartridge. Otherwise, the effective capacity could be reduced significantly. Therefore, the complete process chain from the supplier to the filling of the cartridge has to be considered.

The resin is typically mixed by the supplier in flooded condition by injection of air. After mixing, water will be rinsed and the mixed resin will be filled in sealed containers. The resin is moist and should be kept moist during the complete process chain. The resin is not free-flowing and has to be dosed into the cartridge by a special filling machine. To prove the filling accuracy CT scans should be conducted afterwards showing a very homogeneous and constant filling. This automated process can significantly reduce the costs of such ion exchangers and guarantee a constant quality level of the product.

3 Performance tests

As the levels of ionic contamination and drag-in rates were not known, typical contamination levels, main contaminants and drag-in rates were defined based on literature research for proof-of-concept testing. During the test a stock solution was continuously dosed into the loop and the test was stopped once a breakthrough occurred. The fulfilment of the separation task was demonstrated by means of experimental tests and CFD simulation. The qualification of the service interval depends on the unique application and is done together with the customer, based on field experience.

3.1 Ion Exchange Test Bench

At MANN+HUMMEL a test bench was build up to validate the ion exchange performance. The fluid can be pumped in a loop at flow rates up to 600 l/h. In order to investigate the breakthrough behaviour the test bench is equipped with up- and downstream conductivity sensors, pH sensors, a flow meter and absolute and differential pressure sensors. Different ions in form of salt solution can be injected continuously in the test circuit as contaminant. The test bench is operating at ambient pressure.

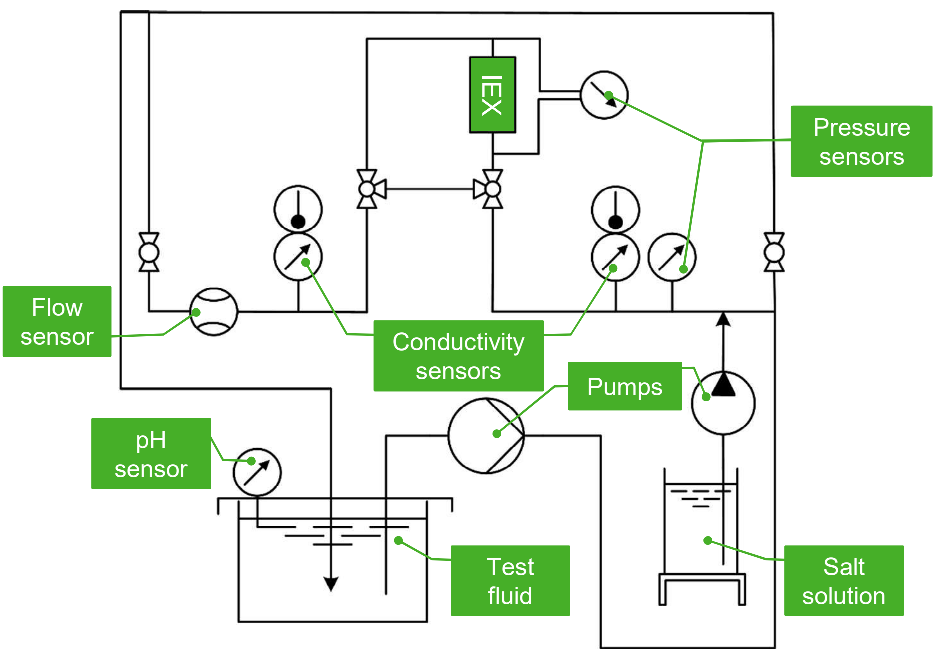

Figure 8: MANN+HUMMEL ion exchange test bench

3.2 Benchmarking

To demonstrate the performance of the new M+H design compared to competitor products benchmarking tests were conducted. Therefore, two competitor products for fuel cell application were selected. In order to investigate the effect of the ion exchanger dimensions two ion exchange columns were build up and tested.

- **M+H design:** Design as described above.
- **Competitor product 1:** This product is an off-the shelf product, where the resin is filled in the housing without any fixation. The cartridge cannot be opened and has to be replaced completely.
- **Competitor product 2:** This product is available as spare part for a fuel cell vehicle. It consists of a pressure resistant, openable housing and a replaceable cartridge containing the ion exchange resin.
- **Short column:** A short column with a resin volume of 250 ml.
- **Long column**: A long column with a resin volume of 250 ml.

These tests were conducted in an external laboratory with a test setup comparable to the M+H setup depicted in Fig. 8. As test fluid the ready to use water glycol mix FC G20 was used at 90 °C. The target flow rate was 600 l/h. In some cases the flow rate was reduced due to high differential pressure of the ion exchange cartridges. As contaminant a LiCl solution was continuously injected in the loop at 0.9 meq/h. The ion dosage is higher compared to what is expected in the field, but has been chosen to accelerate the loading of the cartridges.

The results are showing that all products can keep the el. conductivity below the target value of 5 µS/cm. All products except of competitor product 2 are starting at an el. conductivity < 1 µS/cm. At the end of lifetime a sharp increase in el. conductivity can be seen in all cases. The M+H ion exchanger is showing the highest capacity, whereas the competitor product 2 is showing the lowest capacity.

The comparison of the results of the short and long column are remarkable. The short column was run at a flow rate of ~ 600 l/h, whereas the long column could be run only at 18 l/h due to high pressure losses. Nevertheless, the curves are showing no significant difference, i. e. that high flow rate and short flow length do not adversely affect the effective capacity. This stands in opposition to common design guidelines for ion exchangers, where the flow rate should be kept low and the resin column should be slim and long. The difference to common ion exchange applications is the low ion concentration level. In most tests runs, there was no significant difference between upstream and downstream el. conductivity detectable.

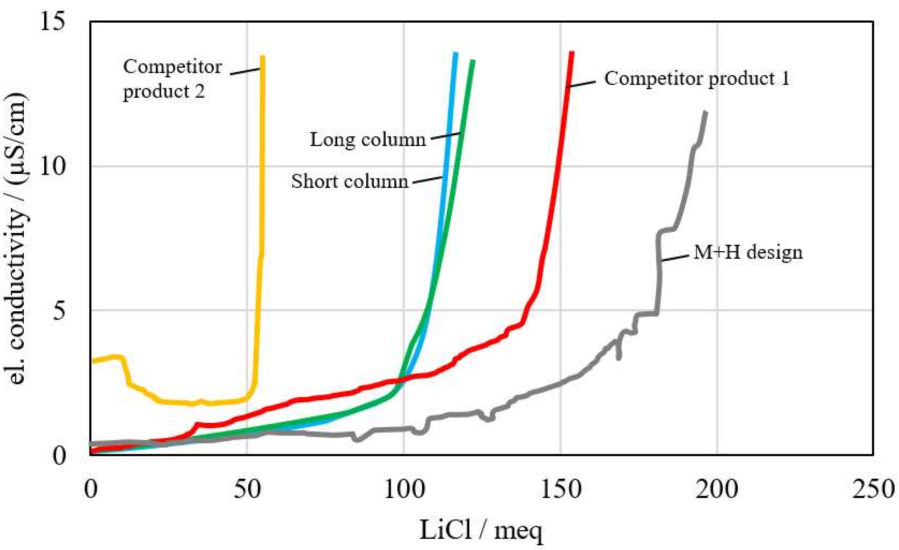

Figure 9: El. conductivity for different ion exchangers

From the tests the following can be concluded:

- The column height can be kept low without adverse effect on the effective capacity. This significantly reduces the pressure loss through the resin column. From Eq. 1 it can be derived that the differential pressure can be reduced by halved resin column height and doubled cross section by a factor > 4.
- The ion exchanger is typically installed in a bypass to reduce pressure losses. The bypass flow rate should be kept as low as possible to reduce the pressure drop. At low flow rates a difference between upstream and downstream el. conductivity will be notable, i. e. with increased loading of the resin the downstream el. conductivity can be still low while the bulk el. conductivity is exceeding the limit value. This effect is more pronounced in case of a gradual breakthrough.

3.3 Simulation

As described above the novel design can be equipped with an optional internal bypass, i. e. only a minor fraction of the flow rate is flowing directly through the ion exchange cartridge. The major fraction is bypassed. Such a design can be beneficial to reduce pressure drop. Furthermore, the ion exchange could be installed in the main flow and an additional bypass would become redundant.

By means of CFD simulation the new design was tested for its capability to bypass the major fraction of the flow rate. The simulation has been conducted with a 2.9 million cells mesh (hexagonal and tetragonal) in ANSYS 19. The properties of a typical water-glycol mix were used in the simulation. The flow through the resin bed was simulated based on a porous media approach, the permeability was calculated from experimental data.

Table 1: Overview of conditions and results

	Test 1	Test 2	Test 3	Test 4
Flow rate / (l/h)	6000	7800	15000	3000
Temperature / °C	90	90	90	0
Over all pressure drop / mbar	332	550	1960	116
Pressure drop across resin / mbar	79	129	426	28
Percentage of flow across bypass / %	95	93	89	99.6

The simulation results show that a fraction of > 90 % of the total flow rate can be bypassed by the current design. For very high flow rates of 15,000 l/h in the main flow the design should be modified, e. g. the inlet and outlet connectors should be increased in diameter to avoid high pressure losses.

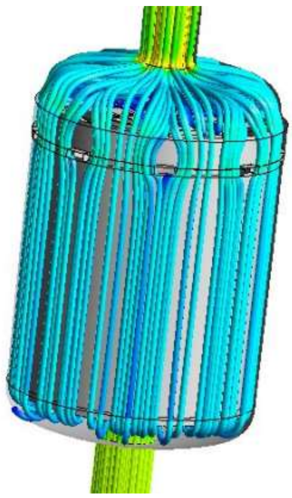

Figure 10: CFD simulation of flow through the ion exchanger

4 Summary and Outlook

In this paper the new M+H ion exchanger design for LT PEM Fuel Cell is introduced. The new design combines high ion exchange capcity and a compact design. The inner cartridge is designed as cost-effective spare part, which can easily be replaced by opening the housing. Optionally, a bypass can be realised to reduce pressure drop or to potentially install the ion exchanger in the main flow. By means of CFD simulation the flow rate distribution for different operating conditions was simulated. The chosen resin guarantees highest effluent purity, highest operating capacity and reliable operation. The used materials for housing and cartridge are optimised for low ion discharge. In a benchmark test with competitor products the new M+H design showed the highest capacity of all tested products. In addition, these tests have confirmed the assumption that the dimensions of the ion exchanger and the flow rate have relatively low effect on the ion exchange performance.

At MANN+HUMMEL a new test setup for validating ion exchangers was built up. This test setup will be used to investigate the effect of different operating conditions on the ion exchange performance and to figure out the optimal operating conditions.

References

[1] Hydrogen Europe, *Zero Emission Mobility,* https://hydrogeneurope.eu/zero-emission-mobility, accessed on 2018-09-25

[2] UNFCCC, *Paris Agreement* (2015), http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, accessed on 2018-09-24

[3] IEA, *Paris Declaration on Electro-Mobility and Climate Change & Call to Action* (2015), https://www.iea.org/media/topics/transport/pariselectromobilitydeclaration.pdf, accessed on 2018-09-24

[4] A. Georg, U. Groos, *Korrosionsschutz in Brennstoffzellen – Chemische Beständigkeit von Komponenten im BZ-System*, HZwei, ISSN 1862-393X, 4(2013), 24 – 26

[5] www.i-2-m.com

[6] M. Harenbrock, S. Diersch, *Contamination Control for LT PEM Fuel Cell Systems*, EVS30 Symposium, Stuttgart, Germany, October 9 - 11, 2017

Authors

Simon Leininger studied mechanical engineering and finished his Ph.D. in the field of severe accidents in nuclear power plants in 2017. He joined MANN+HUMMEL in 2017 as product engineer for fuel filter elements. Currently, he is responsible for the development of ion exchangers for automotive applications.

Andreas Wildermuth studied mechanical engineering and joined MANN+HUMMEL in 2009. He is working in the design department for fuel filter elements and is also responsible for the design of the presented ion exchanger.