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Design and testing of a water management system for LT-PEMFC based on liquid water injection and cathode gas recirculation

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Executive Summary

Dependent on the application, fuel cell systems face different challenges. The primary aim of the project presented is to increase the power density of an automotive system by reducing the size of the cathode air path and adjusting the operating conditions. 1D simulations suggested an approach utilizing liquid water injection combined with cathode gas recirculation could be feasible. This paper presents the development process and test results of a water injection system, the preliminary test results of two different approaches to cathode exhaust gas recirculation and first test results implementing this humidification strategy on a full-scale automotive fuel cell system.

Keywords: Fuel Cell electric Vehicles, Fuel Cell Systems, Auxiliary Components & Sensors, Packaging, Cooling, & Heat Transfer, Environmental Impact

1 Introduction

The longevity and efficiency of Proton Exchange Membrane Fuel Cells (PEMFC) is highly dependent on the moisture level of the membrane and therefore the water management of the fuel cell system. Dry conditions accelerate membrane degradation and decrease proton conductivity, while an excess of liquid water increases the probability of flooding, which prevents the reactants from reaching the catalyst [1].

For mobile applications such as fuel cell electric vehicles (FCEVs) the membrane humidifier has established itself in the industry. These passive systems usually reach a good humidification performance over a wide range of operating conditions and similar materials can be used for both, the fuel cells and humidifier membranes. On the other hand, membrane humidifiers have their limitations. They are relatively large, have a high thermal inertia and water retention capacity and a low degree of controllability which is disadvantageous for applications with dynamic load changes [2]. The degradation speed of the membranes increases significantly above temperatures of 80 °C [3], which leads to the necessity of a charge air cooler to cool the compressed air in medium and high load operating points before entering the humidifier. In combination with other mechanisms, performance can significantly drop over lifetime, which makes membrane humidifiers a probable service item for mobile fuel cell systems [4].

Since the membranes contain per- and fluoroalkyl substances (PFAS) which tend to accumulate in the environment, their restriction is being evaluated by the Risk Assessment Committee of the European Chemicals Agency [5]. Although exemptions are being proposed because of their importance in the clean energy transition [6], their use should be limited wherever possible.

The primary aim of the study is to increase the volumetric power density of a fuel cell system by reducing the size of the cathode air path and optimizing the fuel cells operating conditions to increase the current density in the fuel cells itself. An approach utilizing liquid water injection instead of a membrane humidifier possibly enables the reduction of complexity and elimination of the charge air cooler. Additionally, different designs of cathode air recirculation will be examined to support humidification performance in partial load operating conditions.

2 Water Injection

One method of implementing a liquid water injection is to inject directly into the stack utilizing the excess heat produced by the electrochemical cell for evaporation and providing water vapor at the same time [7,8].

The other approach is to inject somewhere along the cathode air path, preferably after the compressor to utilize the elevated temperatures due to the compression. Hwang et al. [9] for example, demonstrates a very effective humidification system utilizing an external-mixing air-assist nozzle as an atomizer and highlights its advantages in automotive systems due to the smaller size compared to a membrane humidifier. Nevertheless, the presented system still requires a stream of air humidified by a bubbler.

Zhang et al. [10] demonstrates a water injection-based humidifier for a 5-kW fuel cell operating at elevated temperatures. This system doesn't rely on external humidification and reaches maintained dew point temperatures at the stack inlet of above 80 °C for coolant temperatures of 95 °C.

Since an automotive Bosch fuel cell stack is being used in the project, adjustments of the stack are not feasible. Furthermore, to avoid the development of a new injection system, the proposed humidification system is based on commercially available urea dosing components originally intended for the exhaust gas treatment of internal combustion engines.

2.1 Preliminary Testing

Before starting the current project**, Bosch Engineering (BEG)** conducted some simple and hands-on experiments to prove the potential of liquid water injection with the focus on charge air cooling rather than humidification. Liquid water was injected into an airstream driven by an electric air compressor. With variable air pressure, controlled by a throttle valve and monitored by pressure sensors, a total of 9 thermocouples and a humidity sensor were placed along a tube. Diverse fixtures were mounted at position (x) to manipulate the flow (Fig.1).

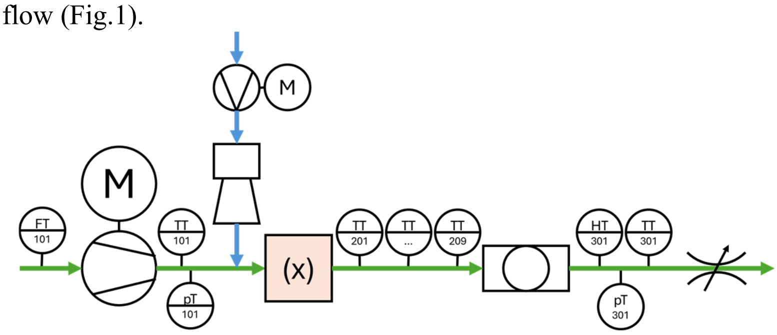
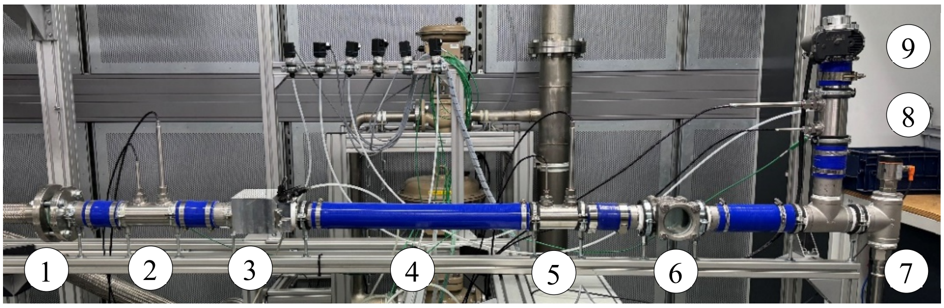


Figure 1: Experimental set-up for preliminary testing of water injection

The experiments show that evaporation of droplets within a short distance is key. Usually, droplets will accumulate on pipe surfaces and run off without evaporating. A well atomized spray consisting of small droplets is beneficial, and so are warm surfaces. Components producing air turbulence and therefore keeping droplets off the walls or forcing liquid water back into the airstream generated the most promising results.

The most promising fixtures were transferred to Fraunhofer ICT, where on a hot-gas test bench more systematic experiments were conducted, also investigating higher air mass flow than was obtainable at the BEG test setup.

To follow up on the investigations conducted by BEG, Fraunhofer ICT set up a test bench depicted in Fig.2. It enables precise measurement of the air conditions before (2) and after (5) the water injection and evaporation path. In case the sensors at position (5) are hit with liquid water, an additional set of sensors is placed at position (8) after an elbow which allows for liquid water separation at (7).



1) Air Inlet
2) Sensor 1 (p, T, rH)
3) Water Injectors
4) Evaporation Path
5) Sensor 2 (p, T, rH)
6) Inspection window
7) Water Outlet
8) Sensor 3 (p, T, rH)
9) Back pressure valve

Figure 2: Setup for preliminary injector and evaporation path testing

The tests conducted include a variation of the injector setup (2-3 injectors injecting at 22.5° and 45° in tubes with the diameter of 50 mm and 100 mm), the variation of evaporation paths (straight tube, automotive catalytic converter, 3D-printed tube structure, steel wool cylinder, gyroid cylinder) and the component arrangement (injection in and against the direction of flow, placement of a vortex tube in front and after the injection).

The crucial factors affecting the evaporation rates are the air and surface temperatures, the water surface (droplet surface and component surface film), the flow conditions at the water surface and the dwell time. To achieve a significant amount of humidification with the straight tube, which served as a reference, a large amount of excess water needs to be injected first and separated from the airstream after the evaporation path. Since no additional water separator at the stack inlet is intended, a tube is not an option. The best results were achieved with components that provide a large surface and allow for cross flow and homogenization along the component. An additional goal was to keep the pressure drop of the component as low as possible to further take advantage of this system compared to a membrane humidifier.

2.2 Water Evaporation Body (WEB)

From the results gathered testing the variants, a selective laser melting (SLM) aluminum body was designed, integrating multiple functions (Fig.3).

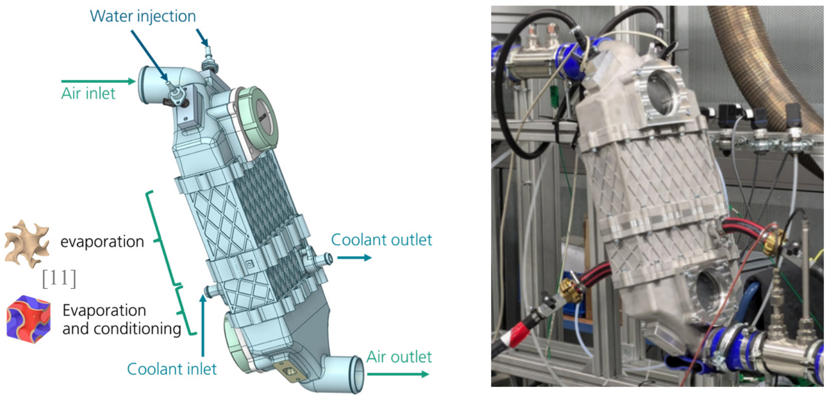


Figure 3: WEB design (left), WEB on the testbench (right)

Two injectors, fed by a commercially available urea dosing system (Bosch Denoxtronic 6-HD), adjustable in angle, are placed on top. The middle part consists of an open face gyroid structure utilizing its large surface, enabling cross flow and liquid water spreading throughout the structure. The bottom section consists of a two volume gyroid structure to have coolant flowing perpendicular to the air stream to either heat up the air and improve evaporation or to act as a charge air cooler. Two glass-covered openings make it possible to visually observe the spray on top and the exiting conditions on the bottom of the component.

A higher amount of injected water generally leads to higher levels of humidification. Since flooding of the fuel cell stack needs to be avoided, exiting water droplets need to be detected. For this experimental setup, the signals of two temperature sensors, one being located directly in the air stream, and one being shielded from direct water droplet impacts, were compared (see Fig.4, top left). For the evaluation of the humidification performance, only operating points were considered in which the unshielded sensor provided a smooth signal.

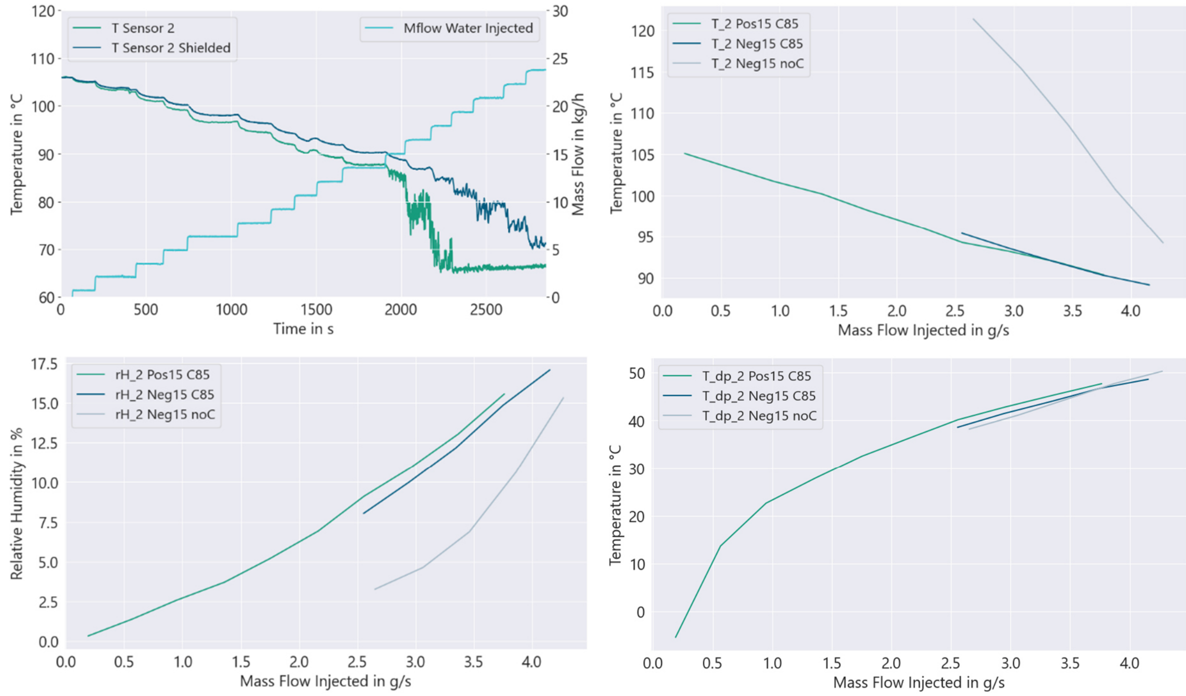


Figure 4: Detection of exiting water droplets for the experiment Pos15_C85 (top left), outlet air temperature (top right), outlet relative humidity (bottom left), outlet dew point temperature (bottom right)

All experiments were carried out at an absolute inlet pressure of 2.9 bar, an inlet temperature of 180 °C and an air mass flow of 500 kg/h, which corresponds to the maximum load operating point of the fuel cell system. Additionally, the angle of injection was varied between positive and negative 15 deg from its basic position (Pos15, Neg15) and the bottom heat exchanger part of the WEB was conditioned with coolant at 85 °C or left empty (C85, noC).

Looking at the cooling performance of the system (top, right), all three variants led to WEB outlet temperatures below 95 °C, which met the requirements, considering that additional heat losses along the cathode path will most likely lead to lower stack inlet temperatures.

Compared to a membrane humidifier, achievable levels in relative humidity are low. Looking at the achievable dew point temperatures of about 50 °C on the other hand, the total water content is similar to that of air exiting a membrane humidifier. This will further be discussed in chapter 4.2.

At a constant injected mass flow of water, the injection angle seems to only have a minor impact. What can be noticed though is that the negative injection angle enables a slightly higher injection rate. These results agree with computational fluid dynamics (CFD) simulations of the injections, trying to optimize the injection settings. An angle of negative 25 deg led to the most uniform wetting of the gyroid structure, considering the interaction of the droplets with the air flow.

Unsurprisingly, turning off the cooling of the WEB leads to a higher dependency of the outlet temperature on the water injection rate. More interestingly, similar amounts of water can be evaporated leading to similar dew point temperatures.

Overall, the performance of the WEB seems promising, especially in the provided, high-load operating point. Due to time restrictions a full performance map could not be obtained yet, and testing continues in the complete fuel cell system (chapter 4).

3 Cathode-Gas-Recirculation

Generally, there are three options to implement cathode exhaust gas recirculation (CEGR) as seen in Fig.5, to directly utilize the gaseous water produced by the fuel cell stack to humidify the cathode intake air.

Option A seems to be the safest regarding the possibility of droplets damaging the compressor blades or flooding the fuel cell stack. On the other hand, it requires an additional component to overcome the pressure drop in the fuel cell stack. Many studies are dedicated to this option. Rodosik et al. for example, examines a 5-kW system under automotive conditions with the focus on relative humidity control at the stack inlet and system efficiency. Key findings include higher recirculation rates leading to better stack stability but worse system efficiency due to oxygen dilution at low and medium loads. High current densities could not be tested due to component restrictions [12].

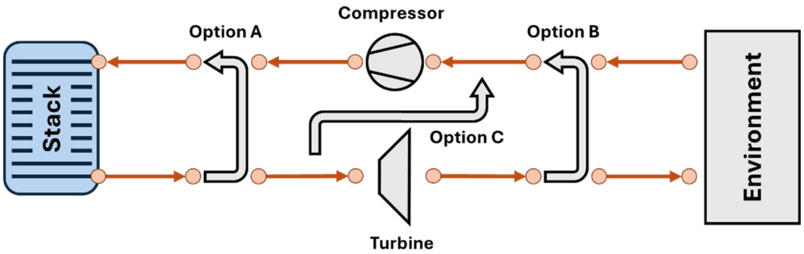


Figure 5: Different setups of cathode gas recirculation

Although less literature can be found examining Option B, Junming et al. suggests it to be a viable alternative to conventional humidification systems in a simulative study [13], although high recirculation rates might pose a problem due to the small pressure difference present.

Option C will work just by controlling a valve in the path, but liquid water will condense due to the high pressure drop and great temperature difference of the mixing airflows and possibly damage conventional compressors.

3.1 Preliminary Testing

Option C:

The simplest option for cathode gas recirculation is shown in Fig.5 as Option C. Humid exhaust gas from upstream of the expansion turbine can be fed back to the fresh air intake driven by a significant pressure difference. Additional hardware is limited to piping and a simple control valve.

Bosch Engineering internal experiments with a fuel cell system operated on a test bench show that, from a functional point of view, the elimination of the membrane humidifier with that method is in essence possible. As is shown in Fig.6 (right), the intake air humidity can be tuned to a specified target value very precisely by adjusting the recirculated mass flow. In comparison, the air exiting the membrane humidifier will be significantly more humid, but with the prospect of a considerable decrease in performance as the membranes age.

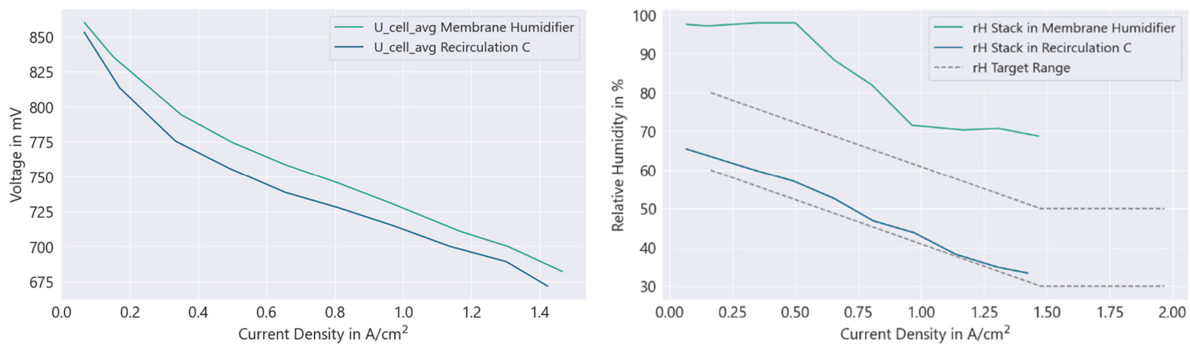


Figure 6: Polarization curve (left) and relative humidity at stack inlet with membrane humidifier and cathode gas recirculation (right)

On the downside, as can also be seen in Fig.6 (left), stack performance will be markedly lower due to a lower oxygen content in cathode air supply. This effect can partly be compensated by elevating the operating pressure but must be considered in system as well as component specification.

Figure 7: Erosion on compressor wheel due to droplet impingement

The main drawback of this kind of recirculation is the additional strain that is put onto the cathode components in general and the compressor in particular. Due to expansion in the recirculation control valve and a temperature drop during mixing with fresh air, water from the formerly saturated exhaust air will condense and enter the compressor in liquid form. A standard untreated aluminum compressor wheel can deteriorate very quickly with damage posed by water droplets (Fig.7). Depending on the bearing concept of the compressor, condensation and wet air might also lead to failure of air-cushioned foil bearings. Most fuel cell compressors today don't support condensing moisture in intake air, so component development becomes necessary.

Option A:

In a second **Bosch Engineering** internal experiment, saturated air from the stack exhaust was conveyed directly to the stack intake using a side channel blower (Fig.5, Option A). A conventional membrane humidifier and charge air cooler were still integrated, but since the bypass was opened completely, only a small amount of fresh air was humidified. With this method, target humidity levels adjusted even more quickly and precisely, evading the pitfalls of putting more load and strain on the compressor. On the downside, additional complex components, like a blower or some kind of jet pump, are necessary to overcome the pressure drop of the fuel cell stack.

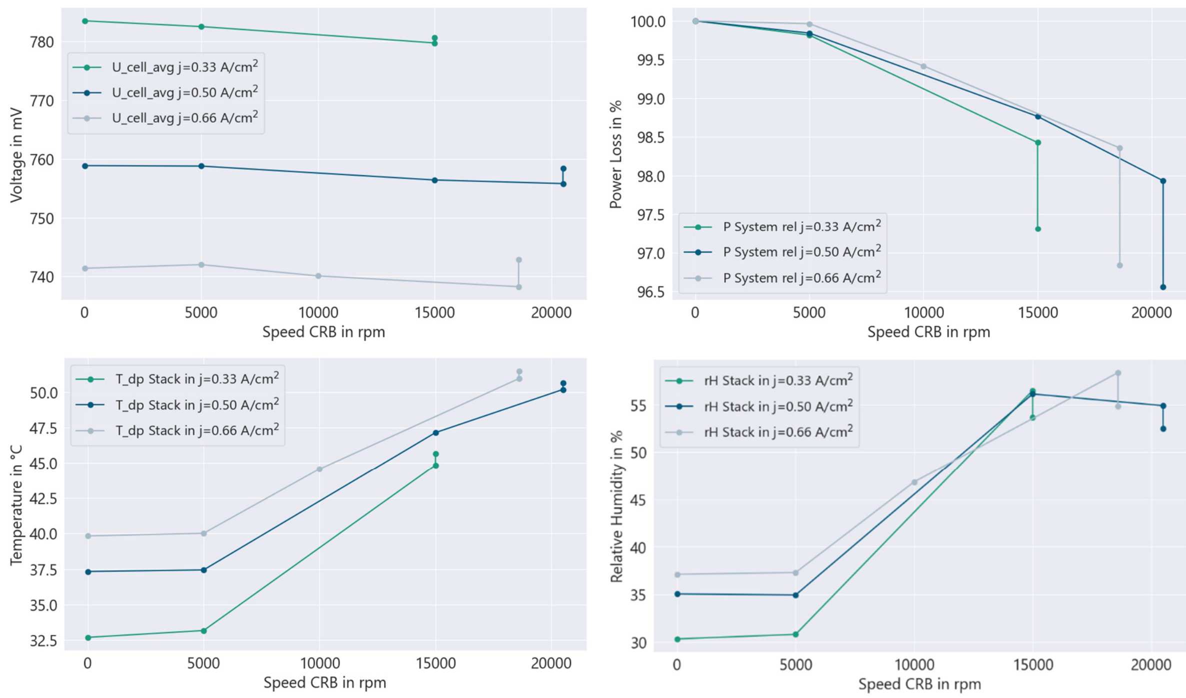


Figure 8: Average cell voltage (top, left), rel. system power loss (top, right), dew point temperature (bottom left) and rel. humidity (bottom right) in three operating points

As with any kind of recirculation, the oxygen concentration of the cathode supply air will decrease and so will, in consequence, stack performance as seen in Fig.8, if no counter measures are addressed. In all three operating points, increasing the recirculation rate lowers the average cell voltage, although the voltage losses are relatively small.

In this experiment, the fuel cell control unit (FCCU) keeps the compressor air flow and the pressure at the stack outlet constant. Therefore, the recirculation leads to higher airflow through the stack, increasing the pressure drop and the pressure level at the stack inlet. The system power therefore decreases due to a lower cell voltage, a higher power drawn by the compressor and the power drawn by the cathode recirculation blower (CRB).

The last result of each test series at the highest CRB speed tested relates to the effort of compensating the voltage loss by increasing the air pressure. It clearly achieves that, especially for higher current densities. When looking at the system power on the other hand, the voltage gain doesn't compensate for the additional parasitic power used by the compressor motor.

Although the recirculation decreases efficiency, it is highly effective in increasing the humidity at the stack inlet for low and medium load operating points possibly reducing membrane degradation.

As will be explained later, recirculation Option A could be a valuable addition to water injection for operating a fuel cell system at the lower end of the power spectrum, when charge air cooling is not needed, the injection humidification performance is low, and the cathode stoichiometry is high anyway.

4 Fuel Cell System Testing

4.1 Description Test Bench System

For system testing, a full-size fuel cell system, based on a Bosch production fuel cell stack, was built and is currently being operated on a system test bench. Fig.9 shows a schematic overview of a fuel cell electric drive, which the test bench system is based on.

The stack itself is designed for heavy duty commercial applications, rated at a relatively low current density of about 1.5 A/cm², and a lifetime 20.000 h or more. For the sake of this investigation a reduced lifetime is acceptable, and the stack is operated to higher current densities although it should be borne in mind that design modifications are advisable for a passenger car application.

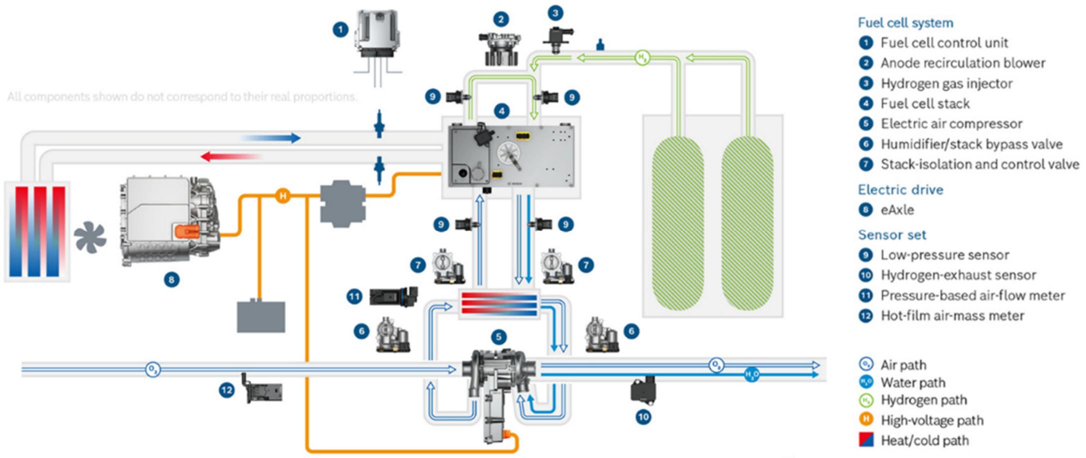


Figure 9: System overview of a fuel cell electric drive (© Robert Bosch GmbH)

Integrated and bolted directly to the baseplate of the stack, the anode sub-system is also based on commercially available Bosch components and adapted for the higher power output. It features active hydrogen recirculation and an electronic pressure control valve. Fuel supply has been realized by the laboratory's hydrogen grid.

Cooling for the stack and balance of plant components is provided by the laboratory's coolant grid. A plate heat exchanger, a controlled bypass valve, an automotive coolant pump and the Bosch fuel cell control unit (FCCU) ensure the necessary constant and adjustable coolant temperature.

In place of the DC/DC converter, HV battery and electric motor of an automotive drivetrain, the power produced by the fuel cell system is fed into the electric grid by a programmable sink, controlled by the FCCU via CAN interface.

For research purposes, the cathode sub-system has been modified heavily to enable a variety of investigations and the verification of the insights gained in preceding experiments. Nonetheless, all components used originate from automotive development and can be used in mobile applications.

Process air is supplied by a 30-kW electric air compressor, equipped with an expansion turbine (Bosch EAC Gen. 2, B sample). As per standard application for automotive fuel cell systems, the stack can be bypassed for start-up and compressor surge protection.

The membrane humidifier and standard liquid to air charge air cooler were removed and replaced by a custom designed Water Evaporation Body (WEB, chapter 2.2, Fig.3).

To gain maximum flexibility, two independent variants of recirculating humid off-gas were realized. While in a high-pressure system (Fig.5, Option A) a commercially available side channel blower is used, a low-pressure option (Fig.5, Option C) can be controlled by a sealed butterfly valve.

4.2 Influence and limits of liquid water injection

The full-size fuel cell system used for researching the influence of water injection and cathode gas recirculation has been commissioned and is in stable operation. Nonetheless, investigation is still ongoing, and all results are preliminary.

In the current research project, water injection is mainly used for charge air cooling, with intake air humidification as a side-effect. The first measurements show that, without considering longevity of the membranes, the system can be run with no water injection up to a compression ratio of about 1.5. Humidity at cathode intake, considering ambient conditions of about 20 °C and 40 %rH, will then adjust to less than 5 %rH, while membrane humidity must be ensured by alternative means like low operating temperature or internal humidification. For higher compression ratios, cooling of the compressed air, in this context water evaporation, becomes necessary, which will also help humidification.

Assuming that enough water is available for injection, flooding of cells by liquid water entering the stack will represent the upper limit as observable in Fig.10. First, the humidity sensor is recording a strongly fluctuating signal and shortly after, when the humidity measured rises to almost 100 %rH, the cell voltage of the first cell is dropping rapidly.

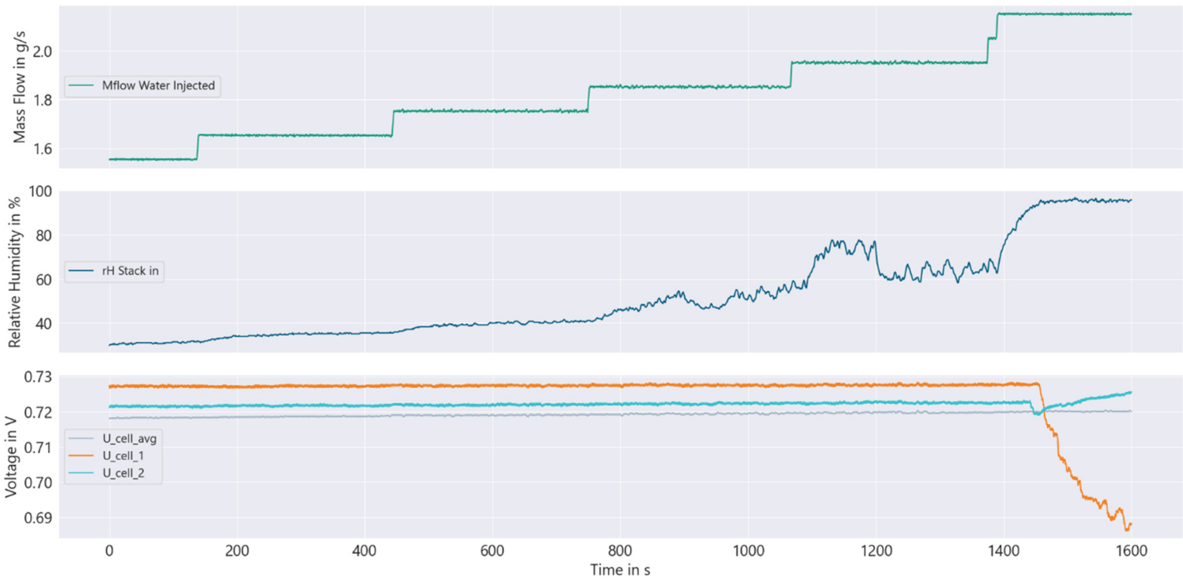


Figure 10: Droplets of liquid water and cell flooding as upper limit for water injection at a current density of 0.8 A/cm^2

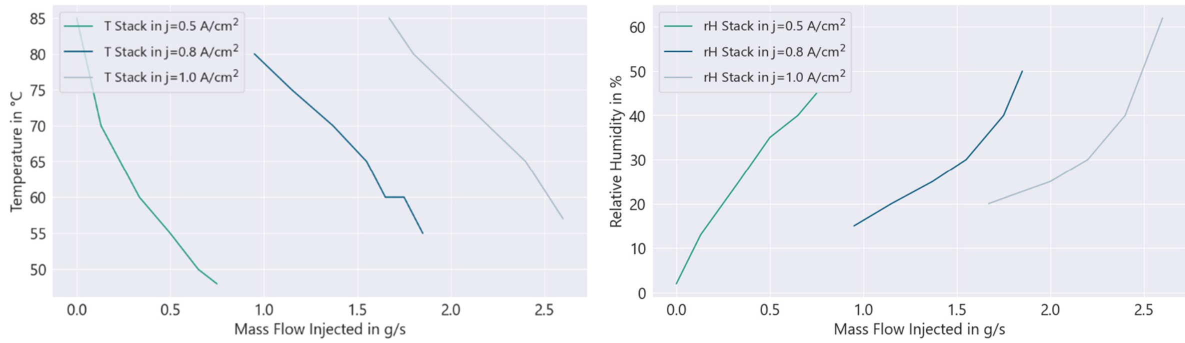


Figure 11: Variation of mass flow of injected water for selected operating points

Fig.11 shows the cooling and humidification capacities of the WEB exemplary for low and medium load operating conditions when trying to find the greatest injected mass flows possible. Increasing with the current density, the pressure ratio of the air compressor increases from 1.7 to 2.1 to 2.4 and the compressor outlet temperature from 85 °C to 120 °C to 140 °C. These injection rates work at steady state conditions but can still lead to flooding when the system is run dynamically. Therefore, a more conservative parametrization was applied to record a reference polarization curve, knowing that there is room for optimization.

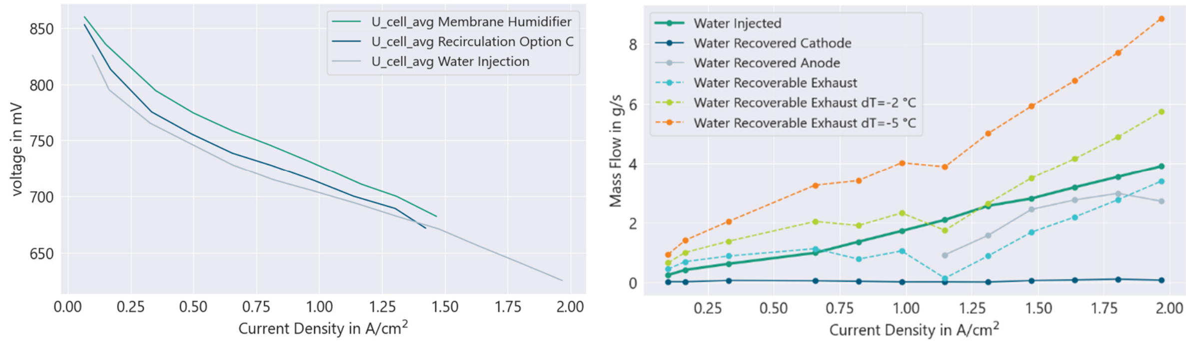


Figure 12: Comparison of polarization curves with different humidification systems (left), liquid water balance for fuel cell system run with water injection (right)

Compared to the other polarization curves, the one measured with water injection shows slightly lower voltages. While the reason for this could be the lower humidity levels in the stack, another cause could be the different stack sizes of the experiments. A greater cell count for this experiment can lead to a slightly worse media distribution in the stack and therefore to a lower average cell voltage. This parametrization will still be tested regularly throughout the test campaign to be able to differentiate between application improvements and stack degradation.

On the right side of Fig.12, all liquid water mass flow rates are plotted. The injected mass flow increases approximately linear with the current density of the stack and needs to be provided somehow. In a vehicle application, a separate water tank should be avoided to circumvent freezing issues at low ambient temperatures. Therefore, recuperated water mass flows from the anode and cathode are being measured and compared to the corresponding injected mass flow. It stands out, that the recuperated water mass flow upstream of the turbine in the cathode path is almost negligible. Most of the produced water escapes the cathode in gaseous form. Substantially more liquid water (between 50-90 % of the water needed for this parametrization) can be recuperated from the stack drain valve and the anode recirculation blower. Looking at the dashed graphs, enough water could already be recuperated downstream the cathode path, when the air temperature drops and water condenses additionally. If the exhaust gas temperature can further be lowered by 2 °C to 5 °C, enough liquid water should be available.

Fig.13 clearly shows the restrictions of liquid water injection. While stack inlet temperatures get lowered to safe levels, the target values for relative humidity can barely be achieved for high current densities (left). The target levels at lower current densities cannot be met with this parametrization. The results from the maximum injection rate experiments represent the limits for optimization at the corresponding current density. Further adjustments will have to be made to the operating strategy to come closer to these limits, while also avoiding flooding during load shifts.

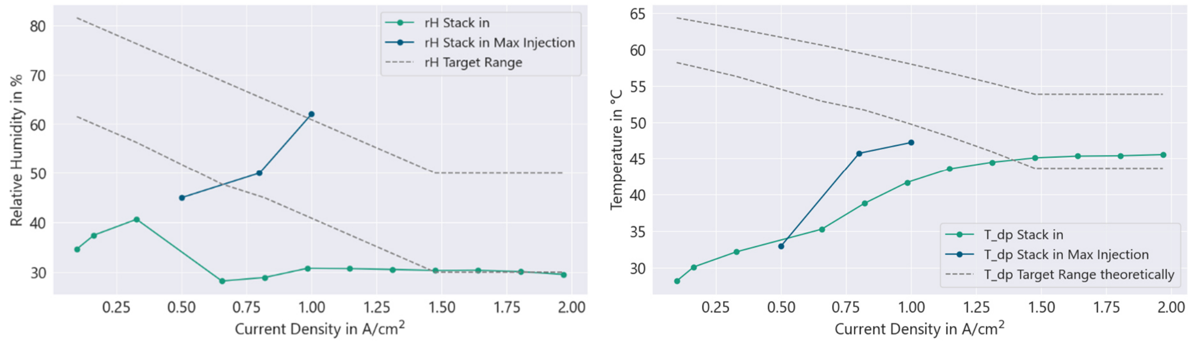


Figure 13: Relative humidity (left), dew point temperature (right) for reference water injection application

In conventional operating strategies, relative humidity is key in assessing the risk of drying out the membrane, since the intake air is conditioned at roughly the stacks' temperature. In this case, since the air temperature can be higher than the temperature of the stack at high loads, one could argue the dew point temperature is as important. Air flowing into the stack will cool down quickly and feature a higher relative humidity. The target relative humidity provided, together with the target stack temperatures, can be converted to a target dew point temperature (right). While this target can be reached at slightly lower current densities, the risk of drying out the first cells and the insufficient humidification level at lower current densities remain.

4.3 Influence and limits of high-pressure recirculation

As mentioned in chapter 3.1, high pressure recirculation can very quickly and effectively adjust the humidity level of the intake air, which can be observed in Fig.14 (top, left). Roughly 5 seconds after changing the rpm of the CRB, changes in relative humidity can be measured. Also, in agreement with the preliminary tests, the cell voltages drop with increasing recirculation rates (top, right), and a small decline in system power output (bottom, right) can be noticed.

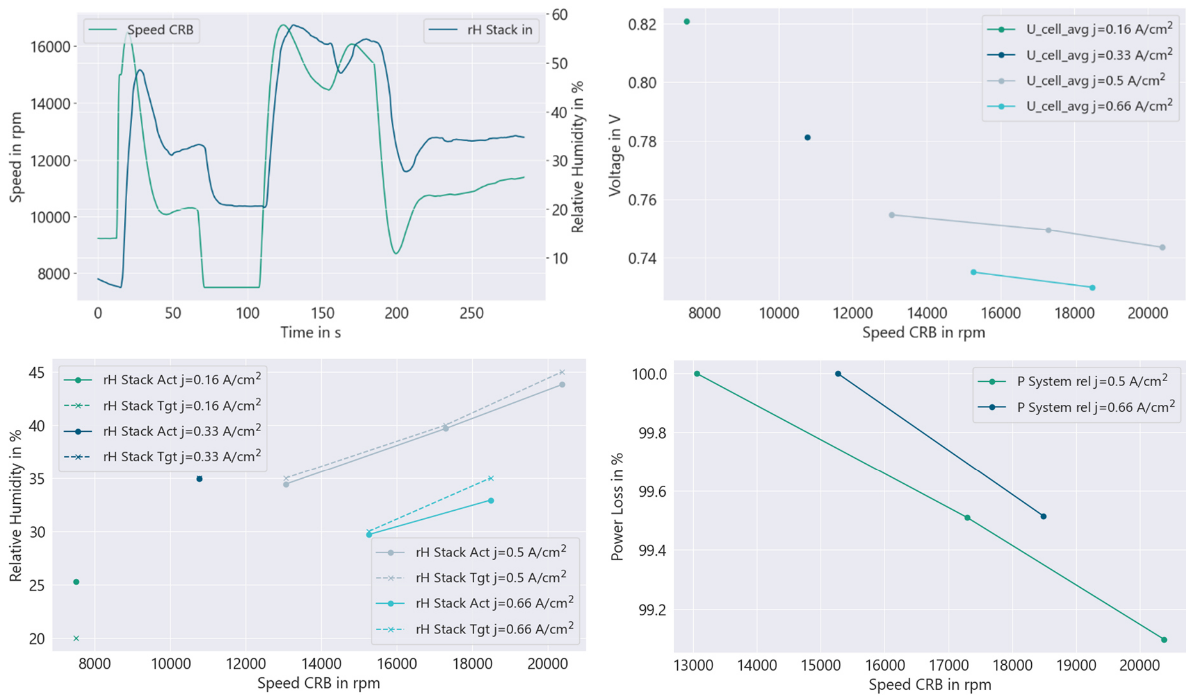


Figure 14: Responsiveness of high-pressure cathode recirculation (top, left), average cell voltages (top, right), relative humidity control (bottom, left) and relative system power loss (bottom, right)

To gather the presented data sets, a target humidity was set in the FCCU and the speed of the CRB was controlled. In the 0.16 A/cm^2 operating point, target humidity was exceeded because the CRB speed cannot be lowered beyond its minimum operating speed. The humidity control works very well at 0.33 A/cm^2 and 0.5 A/cm^2 up to 40 %rH and 0.66 A/cm^2 up to 30 %rH. Higher levels in humidity could not be achieved because of the CRB reaching its maximum speed for the respective pressure difference to be overcome.

4.4 Combined water managing concept

Since liquid water injection doesn't really come with a downside, provided that flooding can be avoided, the injection rate should be maxed out throughout the operating range of the fuel cell system.

As demonstrated earlier, no charge air cooling is required for low load operating points, and only a small amount of water can be evaporated in the WEB. High pressure recirculation is very well suited to elevate humidity to the required levels for up to about 0.66 A/cm^2. Fig.14 (bottom, left) shows that at 0.66 A/cm^2, the target humidity of 35 %rH could not be reached with recirculation alone. A first experiment including water injection showed, an injection rate of 0.8 g/s led to the achievement of the target humidity at about 55 % of the CRBs maximum speed. In general, recirculation becomes more effective with rising injection rates because the water content of the recirculated air rises.

For current densities above 0.66 A/cm^2, the blower used cannot overcome the pressure drop of the stack, but the pressure ratio of the compressor is high enough for the water injection to improve significantly. For high-load operating points, lower levels of relative humidity are more acceptable because of the high amounts of water the stack produces itself.

5 Summary and outlook

5.1 Summary

This paper presents the experimental results of a fuel cell water management system based on liquid water injection and cathode gas recirculation. Starting with a brief overview of preliminary tests on water injection, the developed water evaporation body (WEB) is introduced. The first tests reveal good evaporation cooling performance at high load operating points, while also achieving relatively high dew point temperatures. The preliminary tests of the two types of recirculation tested show, that controlling the relative humidity at the stack inlet is possible. While the variant merging the recirculation upstream the compressor allows recirculation at all operating points, it is not a feasible solution due to the damage caused to the compressor. High pressure recirculation has a very high responsiveness but can only be used for the lower third of the operating spectrum.

The tests carried out in the overall system so far confirm these insights. Furthermore, recuperating enough water for the liquid water injection seems possible although adjustments to the system must be made. The humidity control via high pressure recirculation for low load operating points works well and humidity targets in high load operating points are met via liquid water injection. While the first tests prove a positive interaction of both systems in medium load conditions, a reliable application remains to be a challenge.

5.2 Outlook

Since the project is still ongoing, multiple test campaigns are planned. On one hand, further component tests are planned on a dedicated cathode test stand at Fraunhofer ICT. These include testing the WEB performance depending on coolant temperature, injection angle, air pressure levels and the interaction with low pressure recirculation. Since the recirculated air will pass through the WEB, the interaction differs from the combination with high pressure recirculation.

On the other hand, testing will continue with the whole fuel cell system. These tests include finding the evaporation limits of the water injection for the whole operating spectrum and optimizing the operation strategy for the transition from recirculation to water injection. Additionally, the effects of different stack pressure and temperature settings on the water management will be examined.

Concerning the aim of increasing the systems' power density, final statements cannot be made yet. However, first 3D-CAD packaging concepts suggest an improvement compared to conventional systems. Even more advancements can be made, when the heat exchanger part of the WEB proves to be redundant.

Although this work represents a hands-on approach to the research topic, further research needs to be conducted, especially concerning cell degradation. While eliminating the risk of a degrading humidification system, the conditions of the air entering the stack differ substantially from the conditions in conventional fuel cell systems. Furthermore, the accumulation of substances in the recuperated water used for injection needs to be examined. With the aim of increasing system efficiency, the replacement of the side channel blower in favor of an ejector for the recirculation might be a feasible approach.

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Max Cleven graduated in mechanical engineering at the Karlsruhe Institute of Technology, Germany in 2017. Currently, his research topics include thermal and water management in LT-PEM fuel cells at the Fraunhofer Institute for Chemical Technology ICT in Karlsruhe, Germany.

Peter Eckert graduated in 2004 from Ostbayerische Technische Hochschule Amberg-Weiden, Germany as a mechanical engineer. With experience in the development of heavy-duty trucks and after a couple of years calibrating and testing gasoline engines, he has now been working as a systems engineer in development of mobile fuel cells for Bosch Engineering GmbH in Abstatt, Germany, for the last 10 years.