PEMFC Single Cell concept for the increase in performance through sensor integration

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1. Introduction

Within the development process of PEM (Polymer Electrolyte Membrane) fuel cell components, the different scales of a fuel cell system, like the cell, stack and system level, have to be considered. In this study the design of the IPEK PEMFC Single Cell is presented which allows the analysis of the interaction between the system components and the fuel cell stack itself.

The research focuses on the dynamic operation typical for mobile applications. The dynamic operation is dependent from the change in gas flow on anode and cathode and influences the gradients of temperature, relative humidity, pressure and gas concentration. The IPEK PEMFC Single Cell (Figure 1) is able to emulate the relevant boundary conditions of a complete fuel cell stack to discover potential inhomogeneous gas supply and therefore can support the improvement of performance and lifetime of the PEM fuel cell system.

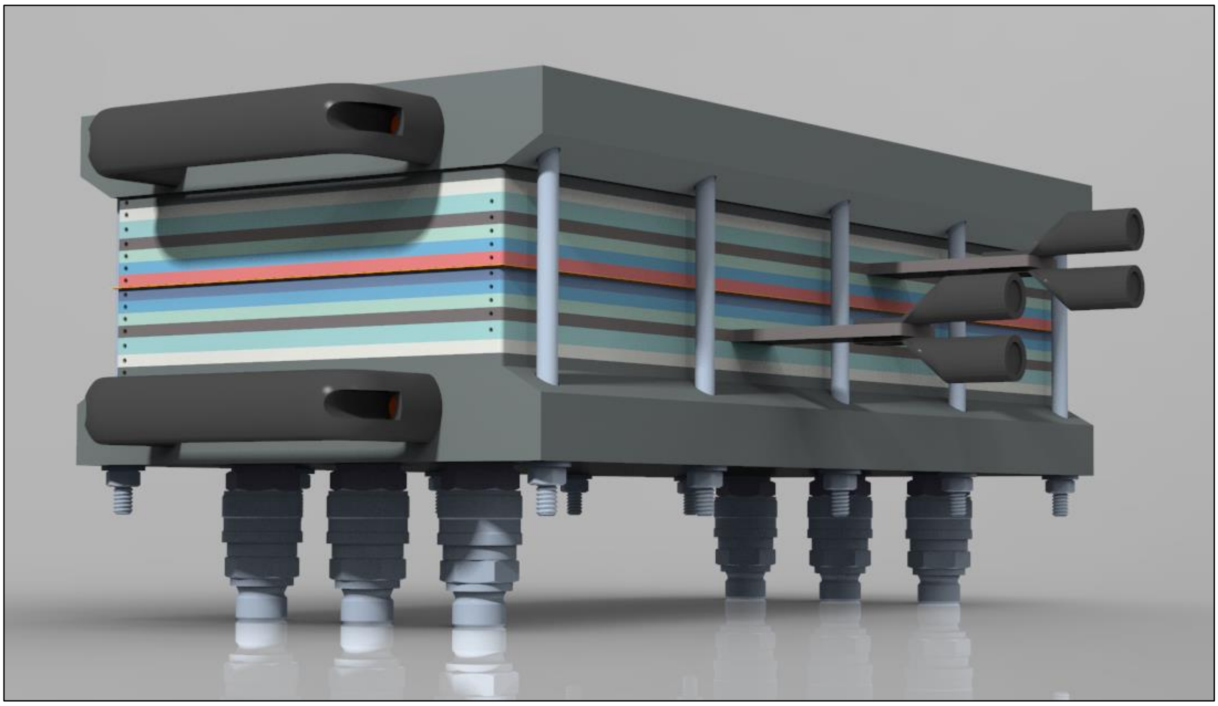

Figure 1: IPEK PEMFC Single Cell which allows emulating the boundary conditions of a complete PEM fuel cell stack

2. Necessity of sensor integration

In mobile applications, the requirements of the drive system for dynamic power provision are usually very high. Depending on the driving situation, short-term power increases can be expected, for example, during acceleration of the vehicle. However, PEMFCs are limited in terms of rapid power supply, especially in dynamic operation, due to the gas dynamics of the system components, such as the air compressor.

The gas conditions change along the gas channels within the active area of the PEMFC – also during stationary operation. However, dynamic load jumps lead to even more inhomogeneous distributions. These gradients include the gas parameters temperature, relative humidity, pressure and gas concentration/ mole fraction on both the hydrogen/ anode and oxygen/ cathode side. In the worst case, the gradients even lead to critical states and thus not only have a negative effect on performance, but also promote degradation.

The distribution of temperature, relative humidity and mole fraction as well as current density along the gas channels during stationary operation were simulated based on the model of Feierabend and Kuschel [1] (Figure 2). The input parameters of the simulation are listed in Table 1.

Table 1: Input parameters for co-flow simulations

Number of cells [-]	1	Cell length [cm]	220
Average current density [A/cm²]	2	Cell width [cm]	127
Cathode stoichiometry [-]	1,5	Anode stoichiometry [-]	1,5
Cathode O_2 concentration [-]	0,21	Anode H_2 concentration [-]	1
Cathode relative humidity [-]	0,5	Anode relative humidity [-]	0,5
Cathode mass flow rate [g/s]	0,33	Anode mass flow rate [g/s]	0,022
Cooling mass flow rate [g/s]	33,66		

In Figure 2 the influence of the gas temperature on the relative humidity during co-flow (hydrogen, air and coolant flow in the same direction) can be observed. With increasing temperature, the gas can transport more water and the relative humidity increases along the channel. However, if a maximum in relative humidity is reached or the temperature drops, water condensation appears. Depending on the gas flow rate, liquid water can accumulate and

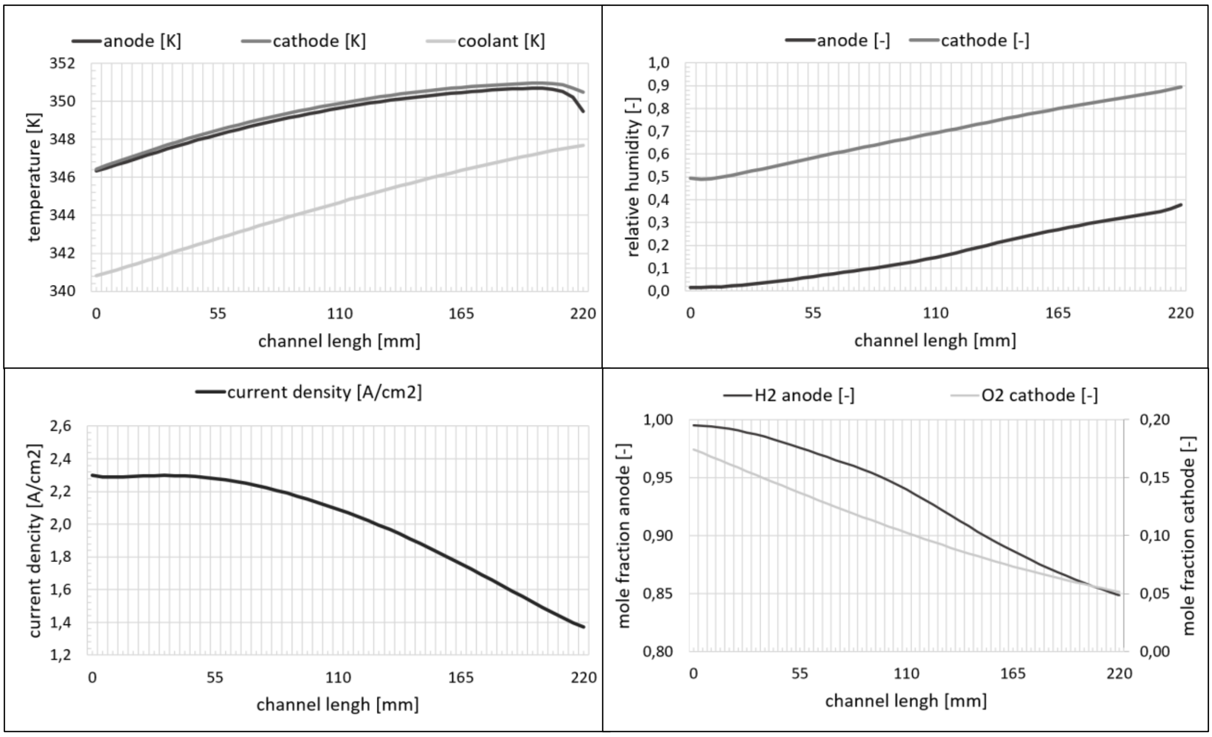

Figure 2: Potential gradients and distributions of temperatures, relative humidity and mole fractions as well as current densities over the length of a channel during co-flow

cause flooding in the gas channels. The liquid water hinders the gas transport of oxygen and hydrogen which results in a decrease in performance of the PEMFC.

In addition, the current density also affects the temperature and relative humidity. If the current density increases, more water is produced due to the reaction of hydrogen and oxygen and the relative humidity increases. With increasing current density typically, the electric power and also the generated heat increases which leads to an increase in temperature. The distribution of the gas concentration has also to be considered for anode and cathode as the hydrogen and oxygen concentration decreases along the channel according to the reaction taking place. With decreasing gas concentration, also the current density decreases.

To achieve a high performance and lifetime also for dynamic operation of the PEM fuel cell system it is relevant to analyze and adjust the gradients towards optimal operating conditions. This could prevent channel flooding and local gas undersupply. Nevertheless, current commercial fuel cell systems only monitor the gas states at the inlet and outlet of the PEM fuel cell (Figure 3). Typically, the gas conditions at the inlet and outlet on the anode and cathode side can be monitored by temperature, pressure, relative humidity and gas concentration sensors. The thermal management system monitors the coolant through temperature and pressure sensors. Thus, the internal gas parameters in the active area of the PEMFC during operation can usually only be estimated.

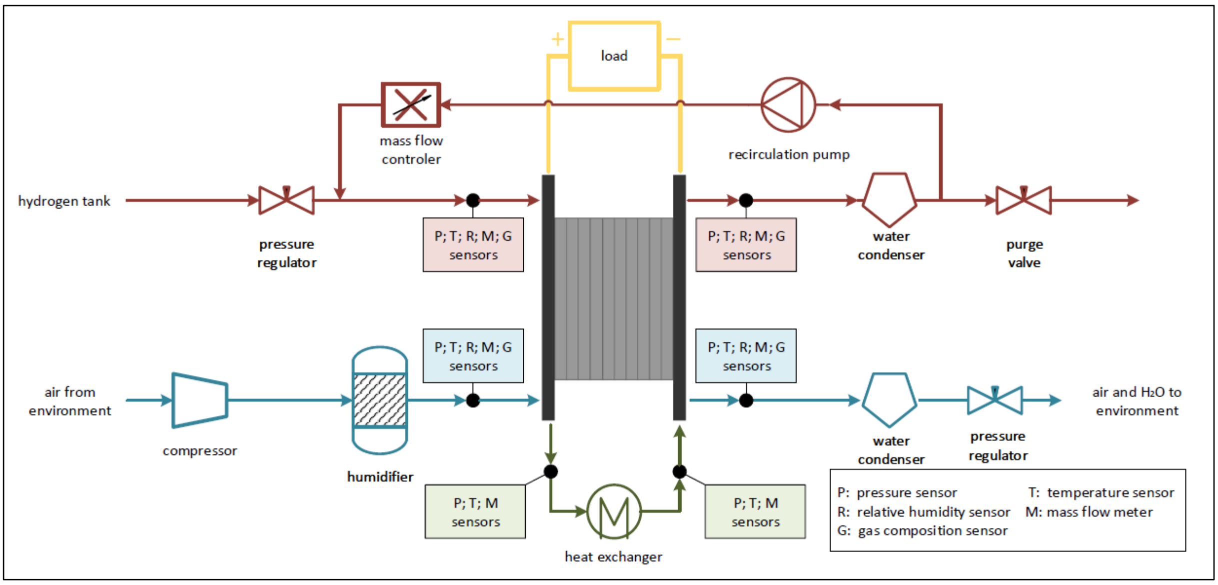

Figure 3: PEM fuel cell system in mobile applications with sensors at inlet and outlet of the fuel cell

However, the observation of the internal distributions of the gas conditions in the active area is of great relevance for the avoidance of local critical states. The IPEK PEMFC Single Cell allows specifically the sensor integration in the gas channels of the bipolar plates and supports the development from research to the actual application.

3. IPEK PEMFC Single Cell

The IPEK PEMFC Single Cell is designed to emulate the relevant boundary conditions of a complete PEM fuel cell stack. Beside the electrical, mechanical and fluid mechanical boundary conditions it can control the local thermal boundary conditions and temperature gradients over the active area by means of an integrated thermal management concept. In combination with a modular design for different compression concepts, all relevant operating parameters can be set individually. Additionally, the IPEK PEMFC Single Cell is specifically designed to detect gradients on the bipolar plate and its gas channels by sensor integration. This sensor concept allows drawing conclusions on optimal operating conditions and helps developing operating strategies for PEMFCs. The key aspects of the IPEK PEMFC Single Cell are explained in the following sections.

3.1. Emulation of relevant boundary conditions of a complete fuel cell stack through an optimized thermal design

The IPEK PEMFC Single Cell consists of two end plates allowing to adjust the mechanical boundary conditions of the bipolar plates in a full stack. The end plate on each side is followed by an isolating plate for voltage protection and to avoid a short circuit via the bolts between the end plates. The electrical current produced by the electrochemical reaction at the catalyst layer within the membrane electrode assembly (MEA) is guided via bipolar plates and the cooling plates to the current collector plates on anode and cathode.

The advanced thermal management system allows the emulation of all relevant thermal boundary conditions of an entire fuel cell stack in just a single cell without actually requiring several hundred cells to be physically present in the test bench.

This is achieved by the combination of cooling and heating plates. While the cooling system discharges the generated heat over the entire active area, the integrated heating pads in the heating plates allow a selective and locally targeted insertion of thermal energy, emulating the thermal boundary conditions of the neighboring cells. In addition, thermal gradients can be selectively adjusted and investigated. The heat flux and the resulting temperature distribution can be seen in the cross section shown in Figure 4.

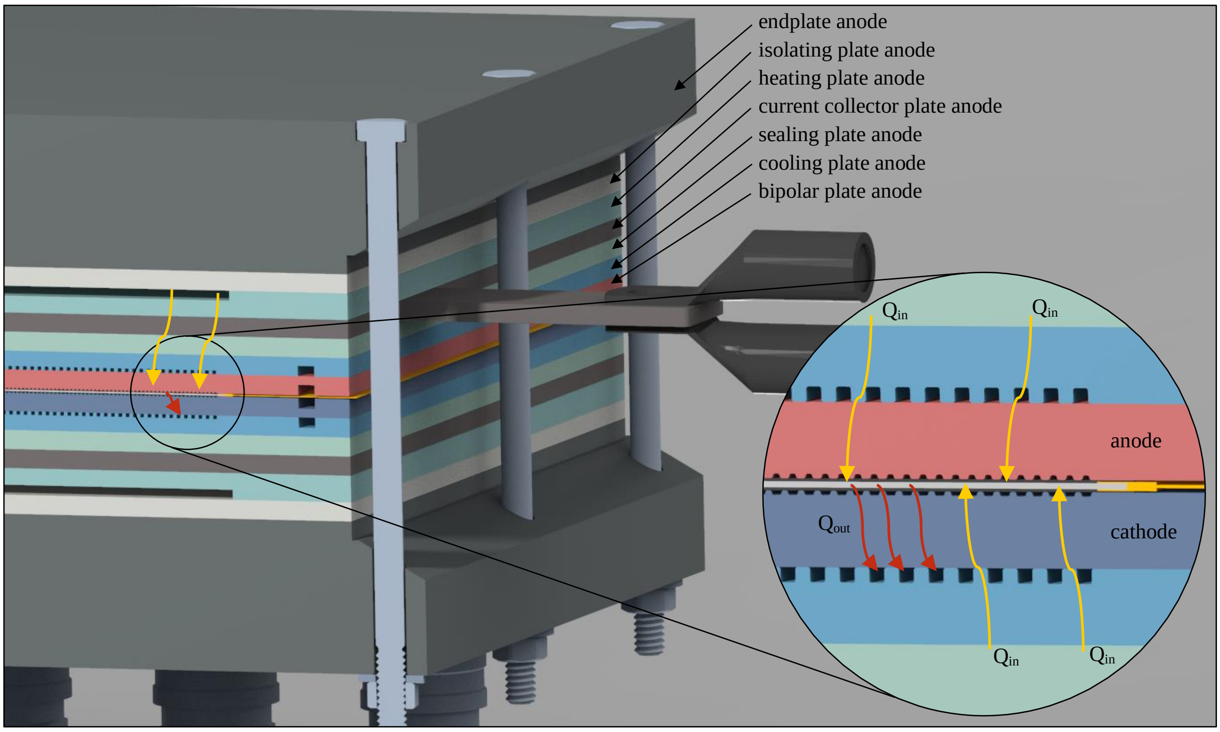

Figure 4: Cross section of the IPEK PEMFC Single Cell with visualization of the heat transfer to the cooling plates and from the heating pads

The design of the heating pad concept and the settings for heating power and cooling fluid mass flow rate for precise emulation of the neighboring cells were developed by applying computational fluid dynamics simulations with the Simcenter™ STAR-CCM+™ software. In the course of these investigations, it was determined that the thermal power of the heating plates has to be set equivalent to the produced heat of the neighboring cells to achieve a comparable temperature distribution with respect to a fuel cell stack (Figure 5). The cross-section of the IPEK PEMFC Single Cell with the temperature distribution from the active reaction area via the bipolar plates and the cooling plates to the heating plates reveals the effect of the heating and cooling sources of the single cell concept.

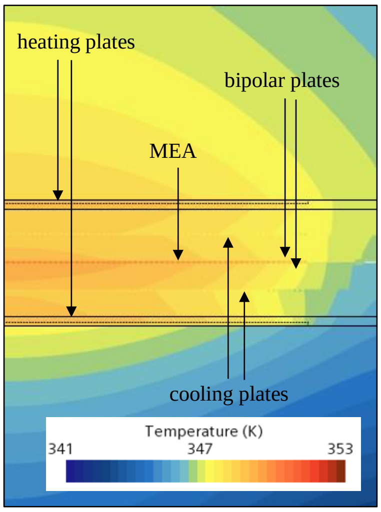

Figure 5: Cross Section of the thermal distribution in a single cell with attached heating pads

3.2. Detection of gradients and critical states through sensor integration

In order to directly detect the gas conditions in the zone of the active area, the bipolar plate is designed to integrate micro sensors in the gas channels. This can be accomplished by placing several sensors from the backside of the active area of the bipolar plate on both the cathode and anode side. The schematic structure of the implementation can be seen in Figure 6.

The sensors are placed in milled grooves on the back of the bipolar plates. The sensor signals of the gas parameters are transmitted by thin wires to the outside of the bipolar plates. This positioning of the sensors has the advantage that the gas conditions that are actually occurring are not falsified by geometric changes of the bipolar plate as a reduction of the cross-section of the channels. In addition, the milled grooves of the sensors and the grooves for

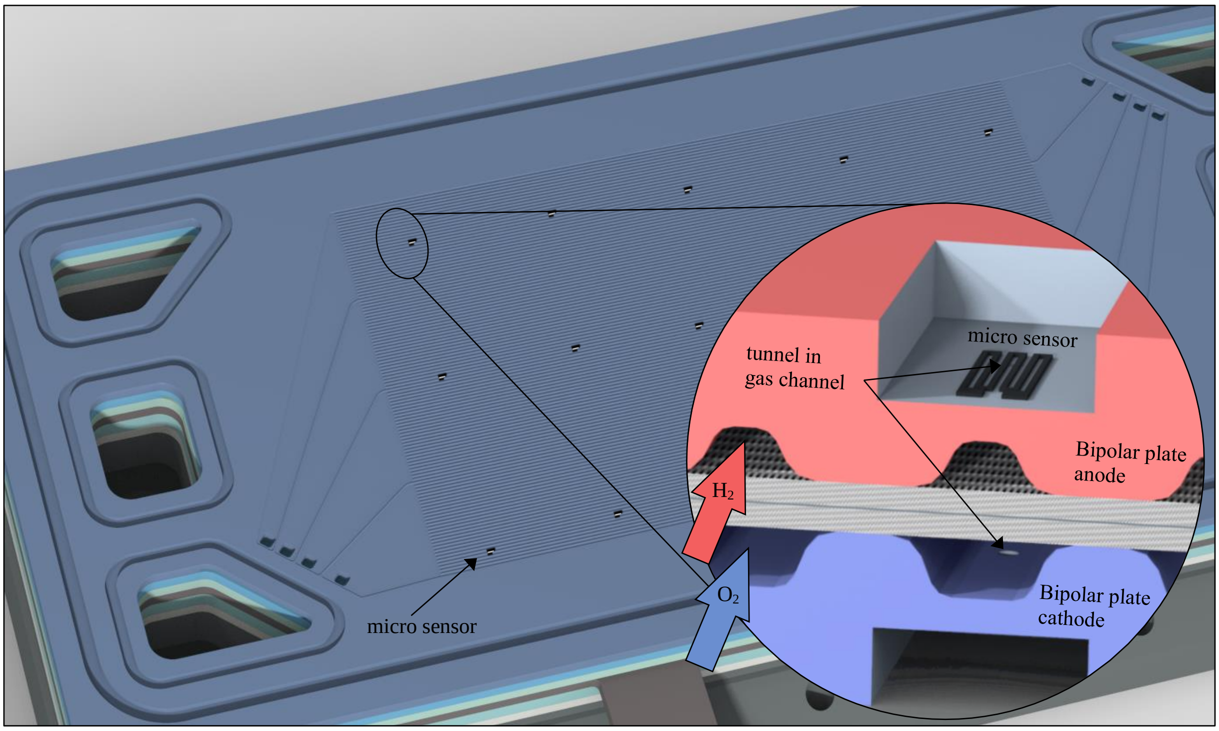

Figure 6: Design and placement of integrated micro sensors in the active reaction area on the cathode bipolar plate as well as their visualization in the cross section on anode and cathode side

contacting them are filled with an electrically conductive epoxy resin. This ensures that the electrical connection is locally not strongly influenced and that the bipolar plate itself and the fuel cell are gastight both internally and externally.

Currently, the main objective is to analyze the temperature and humidity conditions. In a following step, gas concentration sensors will be evaluated for integration to establish a monitoring of hydrogen or oxygen undersupply conditions. Pressure sensors are also promising, but will be more challenging for integration due to their size.

For temperature analysis, resistance temperature detectors (RTDs) (Figure 7) will be used. These sensors offer many advantages due to their small size, high accuracy and short response time, as well as simple manufacturing and excellent durability with regard to corrosion. [2] The measurement principle is based on the increase in electrical resistance when the surrounding temperature increases. [3]

The dependence between the material specific temperature coefficient *α*, the resistance *R* and the temperature *T* is described by equation 1 below. In this context, $R(T_0)$ represents the reference electrical resistance at the reference temperature T_0. [2–4]

$$\alpha = \frac{1}{R(T_0)} \cdot \frac{R(T)-R(T_0)}{T-T_0} \qquad (1)$$

The operating principle of a capacitive humidity sensor is based on the change of the dielectric constant of the sensor material between two electrodes (Figure 8). The measured capacitance is proportional to the relative humidity level present at the sensor surface. [5]

The dependence between the capacitance value *C* and the effective electrode area *A*, as well as the thickness of the humidity sensitive layer *d* between the electrodes and the dielectric constants ε_0 and ε_r is illustrated by equation 2 below. [6]

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \qquad (2)$$

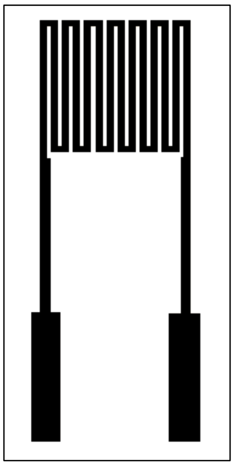

Figure 7: resistance temperature detector (RTD)

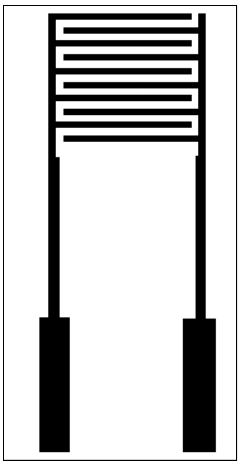

Figure 8: capacitive humidity sensor

Capacitive humidity sensors also offer many advantages in terms of sensor integration of bipolar plates due to their small volume and dimensions. In addition, commercially manufactured humidity sensors are very inexpensive to purchase. [7]

The measurement of temperature, relative humidity as well as gas concentration and pressure can be used to develop improved operating strategies to avoid high gradients also under dynamic load conditions. This allows operating the PEM fuel cell always under optimal operating conditions and increasing performance and lifetime.

After evaluating and validating the sensor integration in the IPEK PEMFC Single Cell concept, the transfer to state-of-the-art metallic bipolar plates will be accomplished. Within the limited space the sensor contacting and signal transmission will be the next challenging step.

4. Conclusion

Especially during dynamic operation, gradients occur in the active area of the polymer electrolyte membrane fuel cell. These gradients describe inhomogeneous gas conditions like temperature, relative humidity and pressure as well as gas concentration distributions. Load jumps and gradients can lead to locally critical conditions. This must be prevented by an optimized fuel cell system control. However, this is only possible as long as the internal parameters within the fuel cell are known.

The IPEK PEMFC Single Cell offers the possibility to measure these internal parameters by integrated sensors to draw conclusions for an optimized operation. Furthermore, the single cell offers the emulation of an entire fuel cell stack through an integrated thermal management concept. This thermal management concept enables the setting of a specific local temperature distribution to analyze the effects of gradients on the fuel cell performance.

The IPEK PEMFC Single Cell offers the possibility to display and analyze all important boundary conditions of a complete fuel cell stack in just a single cell. In addition, the integrated sensors enable investigations of internal parameters such as temperature, humidity and gas concentration gradients. In summary, it initiates the first steps to realize sensor integration in future applications.

5. References

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