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Neutron radiographic in operando investigation of water transport in polymer electrolyte membrane fuel cells with channel barriers

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ABSTRACT

We present a study on a new type of flow field channel design for polymer electrolyte membrane fuel cells (PEMFCs). Small barriers have been implemented into the flow field channels that force the gas flow to move through the gas diffusion layers in order to improve the supply of the catalyst with reactant gases. We investigated the water distribution in the PEMFC with neutron imaging during operation and compared the results with a comparable reference cell without barriers. We found strong hints for an increased mechanical gas flow resistance by the barriers caused by additional liquid water agglomerations. Furthermore water distribution in the barrier flow field is much more homogenous compared to the reference cell. We assume that both effects, namely the gas flow through the GDL and the homogenous water distribution are responsible for the found performance increase of up to 10%.

1. Introduction

Fuel cell technology plays a major role in offering alternative energy supplies for mobile and stationary energy users [1,2]. A common example for mobile systems is the automotive sector, where polymer electrolyte membrane fuel cells (PEMFC) are considered the most favorable fuel cell type because of their high power density and flexible operating conditions [3,4]. Fuel cells can also provide combined heat and electric power in stationary energy systems with a good efficiency [5,6]. However, there are some practical problems that still limit fuel cell use. Especially under critical operating conditions that cause flooding of a fuel cell by product water an optimization of water transport in a PEMFC can lead to an improved efficiency. Such conditions include temperatures below 60 °C as well as high currents that both can cause increased water agglomerations [7–9].

The different materials used in PEMFCs can affect water transport in the cells. Through the material properties the interaction with liquid water during operation influences cell performance. A more detailed understanding of the influence of structural and chemical properties was obtained by analyzing several different materials [10–16]. Flow field patterns machined on bipolar plates are considered one of the most important components affecting the PEMFCs performance. Many researchers have concentrated on improving the performance of PEMFCs through optimization of the channel patterns and dimensions [17–22].

One way to improve both water gas flow and water distribution in a fuel cell is to apply partial blockages to the flow field channels in order to ensure a better supply of the catalysts with reaction gases. Previous studies [23,24] have shown that such blockages spanning a part of the entire cross section of channels can affect the performance of a cell and change water transport within.

Different groups have demonstrated the strong influence of changes in the flow field structure on cell performance. Wang et al. used a flow field structure that is a mixture of serpentine and interdigitated flow fields [17]. They found that interdigitated flow fields show better performance due to convection above the ribs. Perng et al. investigated the influence of obstacles in the gas flow channels on the cathode side on the performance of PEM fuel cells in a computational study [25]. They found an increase in the

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overall cell performance at a cell voltage of 0.2 V ranging between 7.32% and 14.22%. Perng and Wu applied a tapered flow field channel with a baffle plate on the cathode side of a PEMFC for increasing the cell performance [26]. They investigated the cell performance with various gap ratios and taper ratios. They found that the tapered flow channel with a baffle blockage enhances convective heat transfer and flow velocity, which in turn improves the overall cell performance. The maximum enhancement in overall cell performance for various taper ratios while choosing a narrow gap size was 15.5%.

Up to now, the water distribution in such obstacles flow fields has not yet been investigated. Neutron imaging is a measurement technique that provides unique insights into the water distribution in operating PEMFCs [27–30]. Neutron sources such as research reactors and accelerator-based spallation neutron sources produce the intense neutron beams required for efficient and practical neutron imaging. The interactions of neutrons with materials are different compared to X-rays and therefore they can be used in unique ways for nondestructive material testing [27,31]. During the past decades, neutron imaging has been successfully used in many different research fields such as, e.g., engineering, geoscience, soil physics, cultural heritage, magnetism research [32–35]. One of the most important application fields is research on materials for energy conversion or storage [28,36–42]. Aluminium and carbon are nearly transparent for neutrons, while water strongly attenuates a neutron beam. Thus, one can measure the water content in a model PEMFC constructed from the same materials as a real working component. Because of this, many questions related to water management can be studied applying neutron imaging, ranging from the influence of flow field geometry and channel design, freeze phenomena, and properties of gas diffusion media [43–52].

In this study, neutron radiography was used for in-operando investigations of water distributions in the channel system of PEMFCs. A novel approach with partial barriers in the flow field channels that force the reactant gas to flow through the GDL allows for a better supply of the catalyst layer with the reactants. The influence of the flow field channels on the water distribution was studied.

2. Experiments

2.1. Neutron radiography

Fig. 1 shows the imaging instrument CONRAD (COld Neutron RADiography) used for our investigations [53–56]. Neutrons are transported from the 10 MW research reactor BER II to the experiment through neutron guides. The neutron beam at CONRAD is polychromatic with wavelengths mainly between 2 and 6 Å and a maximum intensity at about 3.0 Å. The radiographic measurements of the fuel cells discussed here are performed 10 m behind the end of the neutron guide. The large distance allows for a good spatial resolution of around 200 μm because of the high L/D ratio of 330 when a pinhole of 3 cm diameter is used.

Behind the sample, a detector system consisting of a scintillator, a mirror, a lens system and a CCD camera is positioned as close as possible to the sample [53,54,57]. When the neutrons hit the scintillator, photons in the visible spectrum are emitted. The scintillator used for the radiography measurements was a 200-μm thick lithium fluoride crystal with silver-doped zinc sulfide (^{6}LiF/ZnS (Ag)). The photons are projected onto the camera by a mirror/lens system. The Andor DW436 camera used contains a 16 bit chip with (2048×2048) pixels, each with a size of $(13.5 \times 13.5)\,\mu m^2$. The CCD sensor is continuously cooled to below −50 °C to ensure a thermal noise as low as possible. With the optics used, an imaging field of view of $(108 \times 108)\,mm^2$ with a pixel size of 56 μm was achieved. The pixel size applied is enough to resolve the water distribution inside the cells in sufficient detail. Each radiographic projection is acquired with an exposure time of 2 s.

2.2. Fuel cell setup

Two different cell designs were chosen. In both cases, control of the cell temperature was carried out by using a cooling circuit filled with deuterium oxide (D_2O). Compared to hydrogen, the attenuation coefficient of deuterium is much smaller [27,58–61]. As a result, D_2O hardly attenuates the neutron beam and can only be seen faintly in radiographs. The flow field of the cooling circuit is embedded in the backside of the bipolar plates and is connected with a secondary water coolant circuit via a heat exchanger.

A modified PEMFC was used with a 100 cm^2 large meander-shaped flow field design (two U-turns), comprising a group of 23 channels provided with repeated barriers, which are small regions of the channels of reduced cross sectional areas. The shape and location of the barriers within a flow field channel is schematically shown in Fig. 2A. The channels were 0.8 mm deep and 0.6 mm wide. Between neighboring channels the positions of the barriers are shifted with respect to each other (Fig. 3F), thus enforcing cross rib diffusion, as described e.g. in [62,63]. The modified cell is compared with a cell containing flow field channels of a cross-sectional area of $(0.6 \times 0.6)\,mm^2$ without any barriers (see Fig. 2B).

Cathode utilization curves were performed to investigate the influence of a low gas flow rate on the water content inside the channels and thus on fuel cell performance. The relative humidity was set to a value of 20% at the inlets of anode and cathode for both cells. The product water enriches the humidity to being able to observe liquid water in the channel system. The pressure drop in the cell with barriers has increased from 0.14 to 0.2 bar compared to the cell without barriers. The operating conditions are given in Table 1. Both reference and modified fuel cell showed an almost stable performance down to cathode gas flow stoichiometries as low as 1.1.

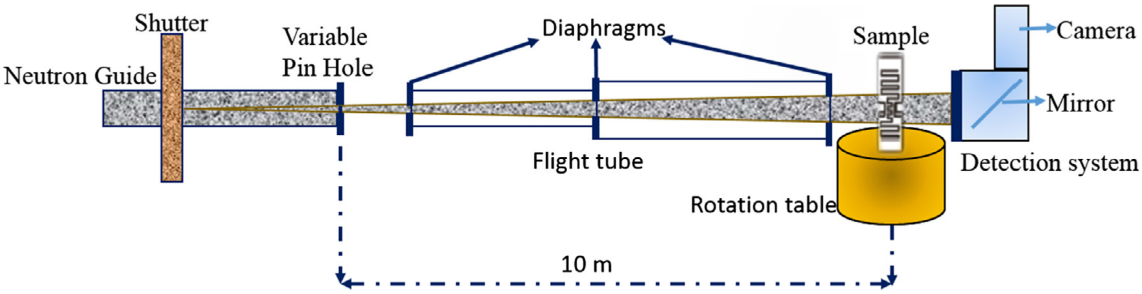

Fig. 1. Layout of the cold neutron radiography beamline ‘CONRAD’.