

RESEARCH ARTICLE

A novel advanced test system for polymer electrolyte membrane water electrolysis based on hydraulic cell compression

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Abstract

In this work, a novel polymer electrolyte membrane water electrolyzer (PEMWE) test cell based on hydraulic single-cell compression is described. In this test cell, the current density distribution is almost homogeneous over the active cell area due to hydraulic cell clamping. As the hydraulic medium entirely surrounds the active cell components, it is also used to control cell temperature resulting in even temperature distribution. The PEMWE single-cell test system based on hydraulic compression offers a 25 cm² active surface area (5.0 × 5.0 cm) and can be operated up to 80°C and 6.0 A/cm². Construction details and material selection for the designed test cell are given in this document. Furthermore, findings related to pressure distribution analyzed by utilizing a pressure-sensitive foil, the cell performance indicated by polarization curves, and the reproducibility of results are described. Experimental data indicate the applicability of the presented testing device for relevant PEMWE component testing and material analysis.

KEYWORDS

high current densities, high operation temperature, homogeneous and reproducible operation conditions, hydraulic cell compression, PEM electrolyzer test cell

1 | INTRODUCTION

Green energy systems especially based on solar, water, and wind energy are identified to help reduce greenhouse gases and reach the 2.0°C average temperature limit as agreed by all parties of the United Nations Conference on Climate Change 2015 (COP 21) as well as the stricter 1.5°C targets described in the SR15 special report by the International Panel on Climate Change. Hydrogen is recently discussed as an environmentally friendly energy carrier of

a renewable energy economy that addresses these targets. When produced from water by electrolysis in combination with renewable energy systems, hydrogen can be a climate-friendly and CO₂-free feedstock for being used as a raw material for the chemical industry and is further meant to be a feasible storage medium for excess energy obtained by renewable energy systems, especially, photovoltaic, wind and water turbines [1–3]. This gains increasing importance when renewable energy systems will be further rolled out and balancing the electrical grids will be necessary due

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to the volatility of sunlight, wind, and water fluxes [4]. Therefore, if electrolyzers are used to follow the energy generation of renewables as well as on fluctuating electrical loads, they need to be operated dynamically. Proton exchange membrane water electrolyzer (PEMWE) technology is ideal for this purpose [5], but further research and development are necessary to optimize performance, decrease costs, and increase lifetime as well as maturity for commercialization at a large scale.

In order to develop and qualify new materials and components, it is important to have a homogeneous and reproducible testing environment. Especially, cell compression and cell temperature have a tremendous impact on cell performance. For larger-scale state-of-the-art stacks, inhomogeneities in cell temperature and cell pressure distribution are caused by inhomogeneous mechanical cell compression [6, 7], and additional efforts need to be undertaken to eliminate or at least minimize these kinds of negative influences [8]. However, it was already reported that alternatively hydraulic cell compression results in reproducible operation conditions for PEMWE stacks. Due to the use of this type of cell clamping, an almost even pressure distribution among the cell's active area is achieved and a nearly isothermal cell operation can be facilitated, if the temperature of the hydraulic medium is controlled in the same manner as the feed water temperature [9].

Here, we report on a newly developed PEMWE testing tool that is based on our earlier achievements in the field of PEM fuel cells and PEMWE stacks. It is designed for benchmarking commercially available materials as well as for accelerated screening of novel materials such as catalysts, membranes, and electrode components, offering valuable scientific output to research and development facilities. The tool comprises a test cell that can be inserted into a pressure vessel with a flexible pocket to clamp the respective cell components via a pressurized hydraulic medium. Due to this design, assembled test cells can be quickly exchanged allowing for rapid testing. In contrast to state-of-the-art PEMWE test cells for material testing which utilize bolts and nuts or a pneumatic actuator, cell clamping is achieved by hydraulic compression, which results in homogeneous operation conditions. Furthermore, due to the principle of hydraulic compression, test results are highly reproducible and can give a meaningful outlook for later upscaling to industrial-scale cells utilizing the same principle [9].

2 | EXPERIMENTAL PROCEDURE

2.1 | Scientific approach

The described test cell was engineered based on research and development results related to PEM fuel cell test sys-

tems with hydraulic single-cell compression [10]. It has been shown that for these PEM fuel cell prototypes current density distribution is homogeneous over the active cell area due to the hydraulic cell clamping. In these prototypes, a hydraulic medium such as water or oil surrounds the active cell components allowing them to control the temperature of the cell resulting in even temperature distribution [11]. In this work, the principles of hydraulic cell compression were adapted to PEM water electrolysis to develop a PEMWE single-cell test system for operation up to 80°C and 6.0 A/cm² corresponding to an absolute current of 150 A.

The introduced PEMWE test system comprises one single cell which is designed to easily exchange the active cell components, namely: pole plates (PPs), anodic porous transport layers (PTLs), cathodic gas diffusion layers (GDL), and catalyst-coated membranes (CCMs). The active cell components fit into a cell frame consisting of two main parts: the anodic and the cathodic half-frame. A CCM is inserted between the two half-frames in a way it is in contact with the PTL and GDL. The PTL and GDL are also integrated into the respective half-frame. Polyetheretherketone was chosen as the frame material, due to its inertness, especially, against the process water as well as the evolving hydrogen and oxygen gases. An integrated channel and gasket system is used to guide process media to and from the active areas on both sides of the CCM. A gasket system made of fluorocarbon rubber protects the test cell against leakage.

With all components integrated, the test cell is still loosely assembled and needs relevant clamping for decreasing the contact Ohmic resistance between the active cell components. For this purpose, the test cell is inserted into a flexible pocket made from polyurethane (PU that is thermally stable up to 90°C), as shown in Figure 1. This pocket is again integrated into a pressure housing, which is filled with silicone oil used as the hydraulic medium. By increasing the pressure level of the hydraulic medium, compression forces are applied to the PPs of the test cell through the flexibility of the PU pocket. As a result, the pressure level is equally distributed over the active cell area and, therefore, cell compression is homogeneous. The pressure housing is designed for a maximum pressure of 10 bar and assessed for tightness up to 20 bar. Furthermore, a heat exchanger is integrated into the pressure housing transferring heat to the hydraulic medium from an external source such as a thermostat. Controlling the temperature and pressure of the hydraulic medium results in reproducible test cell conditions, which can be precisely adjusted. Additionally, as the cell temperature is adjusted mainly by the hydraulic medium, all active electrode materials, for example, the PTLs, GDLs, and CLs can be investigated without using the feed water also for the purpose of cell tempering creating, thus, additional

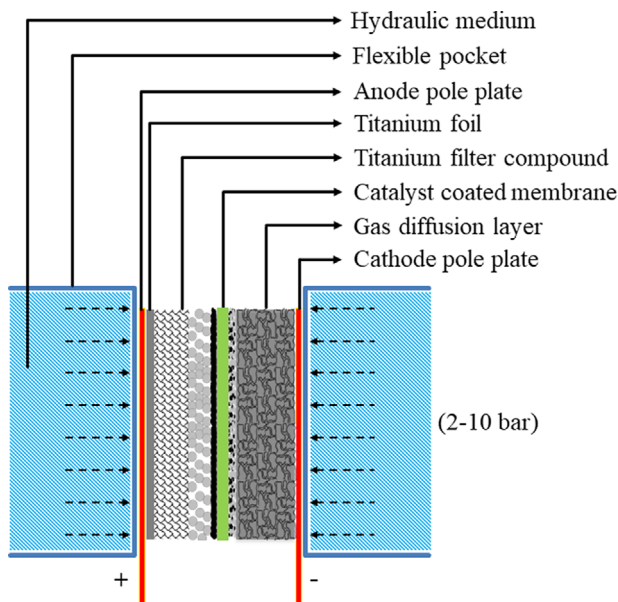


FIGURE 1 Schematic drawing of the developed polymer electrolyte membrane water electrolyzer (PEMWE) test cell

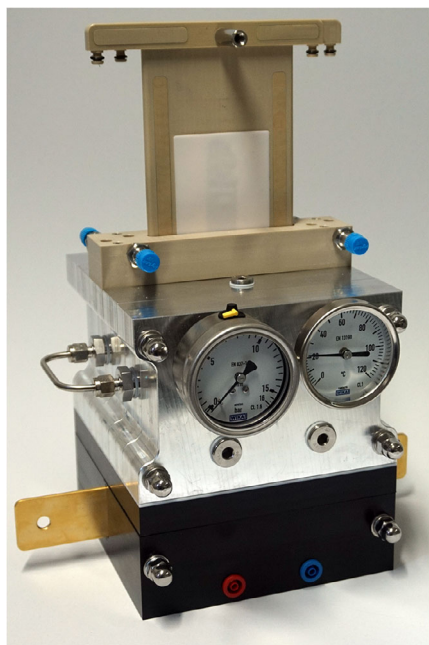


FIGURE 2 Photograph of the novel polymer electrolyte membrane water electrolyzer (PEMWE) test system

degrees of freedom for material developments. Figure 2 shows a photograph of the novel testing device.

2.2 | Materials and methods

Previous to the electrolysis experiments, the PEMWE test system was qualified for homogeneous cell compres-

sion and in-situ operation. A pressure-sensitive foil (type Prescale LLLW by Fuji) that visualizes an impact depending on the applied pressure was used for investigating the pressure distribution over the active cell area. By the resulting image, an impact on a certain area can be differentiated up to 6.0 bar. As PPs, two gold-coated copper plates have been utilized. In order to protect the Cu plate against corrosion at the anode side, a thin titanium foil (grade 1 with a thickness of 25 μm) was placed between the anode PP and the PTL. As the water distribution inside the anode electrode compartment is achieved due to an open PTL structure, PPs are flat and, therefore, do not comprise any flow field.

In situ tests have been performed using a titanium PTL expanded metal sheet sinter filter compound manufactured by GKN Sinter Metals that was recently reported elsewhere [12]. Furthermore, graphitic GDL type Spectracarb 2050A-6060 by Giner ELX and Nafion-based CCMs have been applied as active cell components. Three types of CCMs were used for this work. Utilized CCMs with an anode catalyst loading of 1.0 $\text{mg}_{\text{Ir}}/\text{cm}^2$ and cathode catalyst loading of 0.4 $\text{mg}_{\text{Pt}}/\text{cm}^2$, respectively, were prepared by ultrasonic spray coating (utilizing USI Prism BT) of iridium black (Umicore) and platinum on carbon black (Johnson Matthey HiSPEC 2000) catalyst inks onto a Nafion 115 membrane (N115) following an openly accessible preparation procedure [13]. For comparison reasons, two types of commercially available CCMs based on N115 as well as based on Nafion 117 (N117) were used each comprising the same type of catalyst layer. Further details of the utilized CCMs may not be published as they are subject to the development of the respective company and, therefore, protected by a non-disclosure agreement. They have been chosen in order to have industrially manufactured and comparable material, as in this study, the novel PEMWE test systems were the subjects of investigations. The active areas of the self-prepared and commercial CCMs amounted to 4.0 and 25 cm^2 , respectively. For this work, six individual PEMWE test systems were assembled and tested.

First, the pressure-sensitive foil was used to investigate pressure distribution for clamped test cells. In order to obtain an image of the pressure distribution, cells were assembled including PPs, PTL, GDL, and gaskets. The pressure-sensitive foil with the same dimensions as the CCMs was placed between the PTL and GDL. After the cells were inserted into the flexible pocket of the pressure housing, the pressure level of the hydraulic medium was set to 8.0 bar to clamp the cell components. For each test cell, the same pressure level was used.

Secondly, polarization curves were recorded for each test cell according to the JRC standard procedure described in [14]. The test cells were integrated into a fully

automated test bench, providing separate controls for anodic and cathodic water flow rate, water temperature as well as pressure level and temperature of the hydraulic medium. The tests were performed using ultra-pure water as feed water. Feed water temperature, as well as silicone oil temperature, were set to 80°C, which were measured at the anodic cell inlet as well as within the pressure housing near the elastic pocket that contains the test cell. The flow rate was set to 50 ml/min for the anode side, while there was no water circulation at the cathode side. After a preconditioning procedure, which consisted of applying a constant current density of 1.0 A/cm² for 1 h, polarization curves were measured from 0.0 to 6.0 A/cm² for the test cell with self-prepared CCMs and from 0.0 to 2.0 A/cm² for the tests utilizing commercially available CCMs. A potentiostat/galvanostat type Ivium Vertex.5A with a 100-A-booster was applied for operating the cells with self-prepared CCMs and a power sources type QUEL E2k was used for the analyses of test cells comprising commercially available CCMs.

Thirdly, the influence of the compression level on the cell voltage was investigated. Five individual cells have been assembled utilizing type N115-based commercial CCMs and operated as described at 2.0 A/cm² after the initial break-in procedure at 8.0 bar cell compression. Once a stable operation has been obtained, cell compression was altered in 2.0 bar steps starting at an absolute value of 2.0 bar up to 10 bar and down to 2.0 bar again for two cycles, while the overall current was kept constant at 2.0 A/cm² and at each step the voltage was recorded for 5 min.

3 | RESULTS AND DISCUSSION

The analyses of the pressure distribution at a 6-bar pressure level revealed homogeneous cell compression over the entire surface area of the cells. Results regarding pressure distribution reflect the earlier findings regarding PEM fuel cells with hydraulic cell compression, which were also even and homogeneous [11]. Figure 3 shows representative pressure distribution of the novel PEMWE test cell based on hydraulic cell clamping.

In situ measurements were performed with the test cells having self-made and commercially available CCMs. From the polarization curve recorded using the test cell equipped with a 4.0 cm² self-prepared CCM, a cell voltage of 1.96 V at 2.0 A/cm² can be determined (Figure 4). Further, since the polarization curve is linear in shape from about 0.2 A/cm² at 1.5 V up to 6.0 A/cm² at 2.9 V, it is concluded that there are no transport limitations causing an additional overvoltage with this setup.

For further analyses utilizing commercially available CCMs based on N115 and N117, the test systems were all

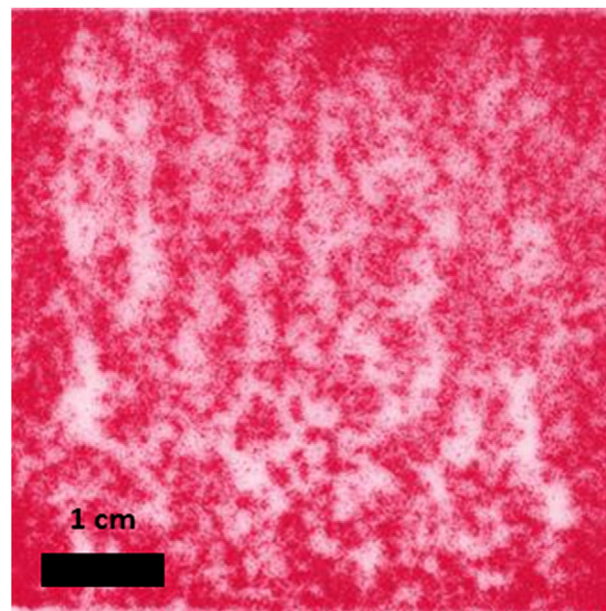


FIGURE 3 Pressure-sensitive foil at room temperature indicating the 5.0 x 5.0 cm test cell's pressure distribution after compression at 8.0 bar

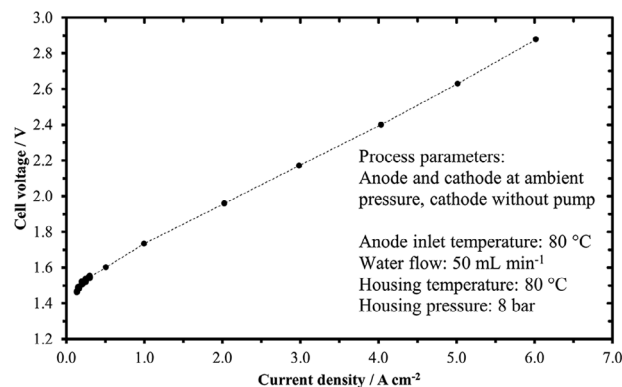


FIGURE 4 Polarization curve up to 6.0 A/cm² of a polymer electrolyte membrane water electrolyzer (PEMWE) test cell equipped with a self-prepared catalyst-coated membrane (CCM) at a working temperature of 80°C and a hydraulic medium pressure level of 8.0 bar

equipped with the same material for PP, GDL, PTL compound, and gasket system. Two test systems were taken for obtaining polarization curves using N117-based CCMs. Four further test systems were used to investigate N115-based CCMs. The obtained results are plotted in Figure 5, whereas the values are in the same range as previously recorded using similar materials but at different temperature levels [12], emphasizing the reliability of large-scale operation.

However, polarization curves recorded using an N117-based CCM do not show a completely linear behavior at elevated current densities. It could not be determined

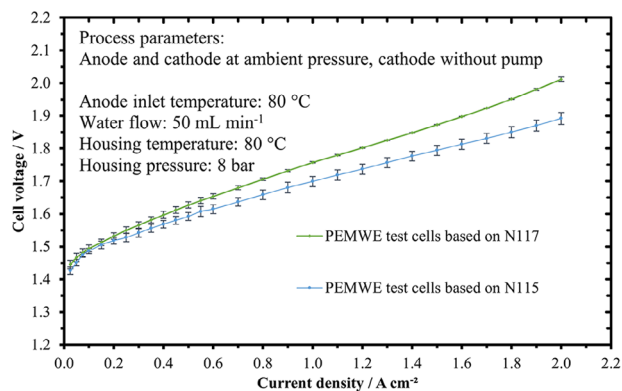


FIGURE 5 Polarization curves of polymer electrolyte membrane water electrolyzer (PEMWE) test cells equipped with different commercially available catalyst-coated membranes (CCMs) determined at an operating temperature of 80 °C and a hydraulic medium pressure level of 8.0 bar

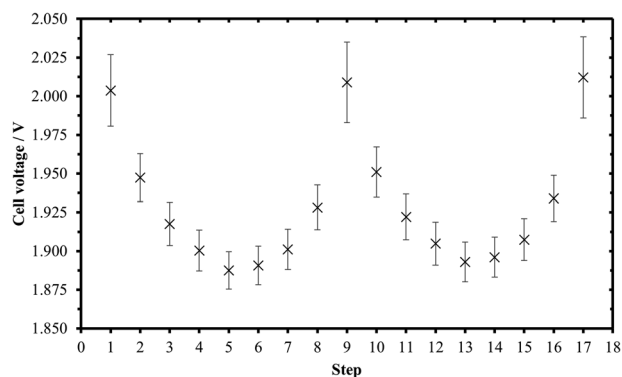


FIGURE 6 Cell voltage of five individual test cells operated at 2.0 A/cm² dependent on the hydraulic medium pressure level represented by 2-bar steps from 2.0 to 10 bar and back to 2.0 bar in two cycles

within this study, whether this is due to mass transport limitations within the PTLs or due to the used N117 membrane. Nevertheless, the results were reproducible and there were no such effects visible in the results obtained with the test cells based on N115 membranes utilizing the same kind of PTL. Overall, the obtained performance data, for example, the determined cell voltage of 1.9 V at a current density of 2.0 A/cm² and an operating temperature of 80 °C is in the range of a recently published study on elaborated Cu-based PPs [15] as well as earlier work such like described in [16, 17].

The influence of different compression levels on the voltage of the PEMWE test cells is presented in Figure 6. As depicted, increasing cell compression does lower the cell voltage at the given setup, whereas the dependence between pressure and voltage is not linear in the investigated pressure range. However, the obtained results

demonstrate the importance of homogeneous and reproducible cell compression for investigations on different materials.

4 | CONCLUSIONS

Due to homogeneous cell compression and cell tempering, state-of-the-art cell components can be evaluated in an advanced cell design. From pressure distribution and electrochemical characterization in the test cells, it can be concluded that PEMWE analyses can be performed in a reproducible manner. The importance of homogeneous and reproducible operation conditions is shown by investigations on the dependence of the cell voltage on cell compression. Hence, presented test cells can be used for comparative in situ analyses of CCMs with new materials, especially membranes and catalysts. Material studies related to newly developed CCMs, PTL, and PPs are the subjects of ongoing project work and will be described and published in a later step.

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