Promoting and Advancing Hydrogen Fuel Cell Technologies:

The Open Fuel Cell Design Platform as an Open Hardware Initiative for Research, Development, and Education

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Abstract: The "Open Fuel Cell" (OFC) is an open hardware initiative of the Chairs of Energy Technology and Manufacturing Technology at the University of Duisburg-Essen and the Hydrogen and Fuel Cell Center ZBT. We documented the manufacturing of a passive proton-exchange membrane fuel cell (PEMFC) using easily accessible materials and instruments, such as 3D-printers and computer numerical control (CNC) milling machines. Materials and construction protocols can be downloaded at https://openfuelcell.org/. The OFC can be operated with a commercially available small hydrogen storage container. While the OFC can be used to operate low power electrical consumers (LED light strips, small fan) the main purpose is to offer a low-cost experimental environment to explore the electrochemical correlations of a PEMFC as well as the engineering involved in the construction and design of such a cell and thereby to spark the fascination for hydrogen technologies. However, we are confronted not just with inquiries from schools but also from universities of applied sciences. Their funding often does not allow to purchase standard fuel cell test rigs and they intend to use the OFC both in research and teaching. We present the OFC as an open science platform on which schools, universities, maker spaces and businesses can build upon. We hope to have launched an open hardware system that grows through community contributions, propelling a fast transition to a carbon-free energy system.

Keywords: open source, open hardware, open science, fuel cell, hydrogen technologies, energy science, PEMFC, additive manufacturing.

1 Introduction

Hydrogen technologies are crucial for decarbonization of the energy sector. However, the ramp-up of hydrogen technologies is slowed down by several factors, an important of which is the lack of qualified employees [1]. An efficient way to spark the interest in technology is to offer hands-on experiences for school and university students. Available fuel cell kits for educational purposes, however, usually come as a "black box" with the functional components not being accessible. Thus, critical engineering aspects, such as the design and manufacturing of individual components and assembly of the cells, are not addressed by most existing educational kits [2, 3]. In contrast, the Open Fuel Cell (OFC) represents a full open source construction manual and kit for the assembly of a simple proton-exchange membrane fuel cell (PEMFC). Most materials and instruments that are required for building an OFC can be easily sourced by hobbyists or schools. Machines used in OFC manufacturing include a 3D-printer, a computer numerical control (CNC) milling machine, a galvanization bath with DC power source and a pressure controlled hydraulic press.

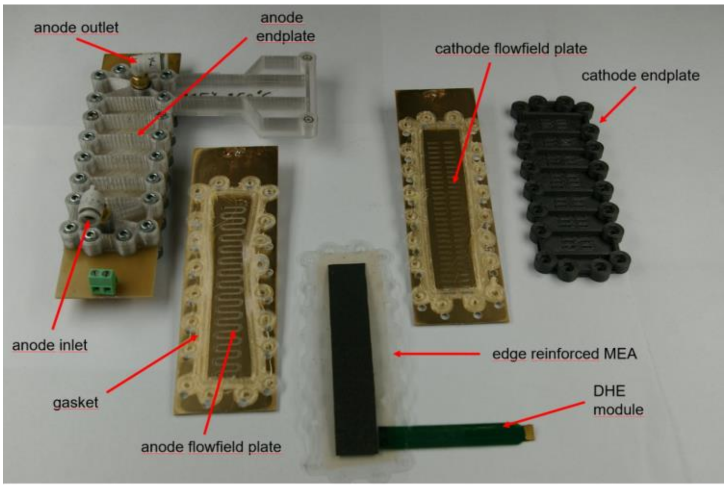

Fig. 1. Components of the open fuel cell.

Notably, the OFC was originally designed for research purposes when fuel cell test bench capacity could not meet the demand for the multiple ongoing research projects in The Hydrogen and Fuel Cell Center ZBT. As a solution that was feasible to be implemented in short term while meeting all the requirements of an applied research project, the OFC was developed in multiple iteration steps. The current configuration incorporates many design features found in mature cells used in technical applications. As a result, prototypes of the OFC have already been employed as the primary cells in a comprehensive research project aimed at developing additional reference electrodes integrated within the cell itself [4]. Therein, the OFC was proven as an instrument feasible to conduct fuel cell related research projects at low costs.

Thus far, addressing similarly advanced research and development aspects in hydrogen technologies required substantial investments and thus represented a financial burden that is difficult to bear for schools, technical colleges as well as small institutes or businesses. Thus, the OFC closes a gap between educational kits and professional solutions in hydrogen technologies.

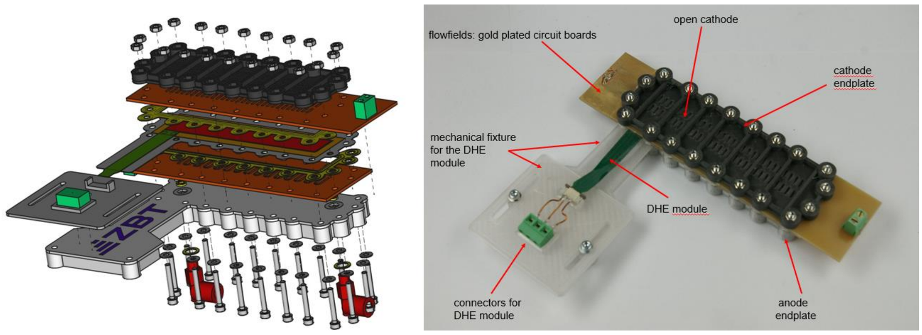

Fig. 2. Exploded view of the open fuel cell components and their assembly (left) and assembled open fuel cell (right).

The primary objective and future plan for the OFC project is to maintain all design plans as open source. Most of the OFC components can be made in a hobbyist's workshop using the simple machines mentioned above. Comprehensive instructions are provided, covering the manufacturing process of the cell, various modifications to meet specific experimental needs, and a discussion board for fuel cell enthusiasts to share results and experiences [5]. The OFC aims to facilitate experimental exploration of all aspects of fuel cell technology. With the optional dynamic hydrogen electrode (DHE) the electrochemical potentials of the anode and the cathode can be determined. Since the purpose of the DHE is to just give a constant reference potential, the anode potential determined with reference to the DHE is assigned to be 0 V_{SHE}. From the correlation of the cell voltage being the difference between the potentials of the cathode and the anode, the according cathode potential can be calculated.

2 Materials and Methods

2.1 CAD Design

All components of the OFC were designed using FreeCAD [11]. All design files including the derived STL and STEP files for further processing using 3D-printer and milling machines can be downloaded from the project homepage [5].

2.2 Pressure Plate Printing

For the production of the pressure plates, a material-saving design was selected that is suitable for the additive manufacturing processes material extrusion (MEX) or bath-based photopolymerization (VPP), commonly known as stereolithography (SLA). For VPP, the pressure plates of the OFC were printed with a standard clear light-curing resin on a Form 3+ (both Formlabs) using a layer height of 100 µm, then post-hardened in a UV oven for gas-tightness. For MEX, PETG (polyethylene terephthalate-glycol) filament was used for the end plates due to its good processability, high strength and durability. PETG filament (Filament4Print) was used to print the MEX plates on a Prusa MK4 printer, with the layer height being set to 200 µm. A filling density of 100% was selected for the pressure anode plate to achieve gas tightness. For the cathode plate an infill density of 50% was used to save material.

2.3 Flowfield Plate Milling and Electroplating

The OFC flowfields consist of printed circuit board (PCB) material. We used Bungard 030306E33 base material one-sided 35 µm photo coating (Conrad). Plates were milled using a Stepcraft D600 CNC Machine and a diamond-coated milling head with a diameter of 1.6 mm (Fig. 3A). The following settings were used: feed rate 5 mm/s, height feed 0.5 mm and spindle rotation speed 2000/s.

After milling, the flowfields were electroplated using Electroplating Unit Comfort II (Jentner). First, a nickel coating was applied (Adhesive Nickel Bath JE303, Jentner). After drying, the plates were coated with a gold electrolyte (Gold Plating Bath JE250 - 5 g/L Au, Jentner). The current was adjusted to a level at which bubble formation became clearly visible in the electrolyte bath which occurs at a voltage of about 2.5 V. Plates are then kept in the electrolyte bath, usually for about 60 s, until a clear deposition of material is observed (see Fig. 3B for nickel coating).

2.4 Gasket Printing

The gaskets were manufactured using a Prusa MK4 3D-printer with a TPU filament possessing a Shore hardness of 70A. This flexible material ensures gas and water tightness, essential for fuel cell gaskets. Specific processing considerations for the MEX additive manufacturing process include reduced filament transport speed and the use of a direct extruder, which minimizes the distance between the feed unit and the nozzle, thus avoiding compression issues common with flexible filaments in Bowden extruders. The gaskets were produced at a speed of 20 mm/s with a layer height of 100 µm and 100% infill.

2.5 MEA Fabrication

As a first step of MEA fabrication, gas diffusion electrodes (GDEs) are prepared. For this, a catalyst dispersion is prepared with the following components: commercially available catalyst (Pt on carbon black, 40% Pt/C), 14.5 ml of water, 7 ml of isopropanol, and 1.2 ml of commercially available ionomer solution (ca. 800 EW). The mixture is sonicated using an ultrasonic bath (Bandelion Sonorex Digitec) to ensure homogeneity. The dispersion undergoes further sonication with a sonotrode device (Branson Sonifier IIISFX250) at 3 different amplitudes, for several minutes at each amplitude. During this process, the beaker must be adequately cooled to prevent overheating. GDE sheets are produced from gas diffusion systems (GDS) sheets by using an ultrasonic coating system (ExactaCoat, Sono-Tek) in which the dispersion is uniformly sprayed onto the Microporous Layer (MPL) side of a GDS.

For the membrane preparation, the membrane has to be edge-reinforced. This is achieved by sandwiching the outer edges of the membrane between two frame type sheets of office supply foil and subsequently ironing the frames on the membrane with a small hand iron. The assembly of the MEA is completed using a hot press (VOGT Labo Press 300S). The layers are arranged as follows: between extra layers on both sides of the "MEA component stack", which help to get to a uniform pressure distribution, the edge-reinforced membrane is placed between the two GDEs prepared before. A protective film, larger than the membrane and its reinforcement frames, is positioned over the assembly. Metal plates, again larger then the protective film, are placed on top, followed by another compressible pressing pad on each side. The entire assembly is centered in the hot press and subjected to a pressure of 1 kN (for 15 cm2 active MEA area) at 140 °C for two minutes.

2.6 Assembly of the Cell

The assembly process of the cell involves a sequence of precise steps to ensure optimal performance and durability. The process begins by inserting M3 screws and washers (25 mm) into the anode plate. The plate is then oriented so that the screws point upwards, allowing other components to be layered on top. The mini gaskets are placed into the designated holes on the anode plate.

Next, the anode flowfield plate is positioned on top of the anode plate, with the flowfield facing upwards. The large gasket is placed on top of the anode flowfield plate, ensuring the ridge is oriented upwards. The gas diffusion layer (GDL) is then added centrally within the large gasket, followed by the careful placement of the MEA on top of the gas diffusion layer. Another layer of GDL is added on top of the MEA. The second large gasket is positioned on top of this layer, with the ridge facing downwards. The cathode flowfield plate is placed on top of the second large gasket, with the flowfield facing downwards. Finally, the cathode pressure plate is positioned on top of the cathode flowfield plate.

The screws should protrude slightly through the entire assembly, and the nuts are then secured onto the screws. The assembly is flipped over, and the screws are tightened in a cross pattern to ensure even pressure distribution, tightening in steps to a torque of

1.5 Nm (Fig. 3D). Subsequently, the medium-sized gaskets are placed around the threads of SMC connectors, which are then screwed in. Gas-tightness of the cell is tested in a water bath to ensure proper sealing (Fig. 3E).

2.7 Operation

The OFC operates in a "dead end" configuration. An exit/purge valve is connected via a 6 mm tube to the gas connector near the optional reference electrode. The hydrogen supply at ~100 mbar connects to the other SMC connector with the purge valve closed. Small metal hydride tanks like the HYDROSTIK PRO (Horizon Fuel Cells) are used for educational use.

For I-V curve measurements, an electronic current load with a 0 V option is recommended. The negative pole of the current load connects to the anode flowfield's electrical connectors, and the positive pole to the cathode's connectors. Using the load's SENSE wires to measure cell voltage directly at the flowfields avoids voltage drops due to cable resistance and connections. If the OFC has an integrated DHE reference electrode, a constant current source should be connected as a DHE-driver. The local anode potential is measured with a voltmeter connected between the OFC anode flowfield and the DHE-driver.

Upon briefly opening the purge valve, time dependence of the cell voltage and anode potential (Fig. 5) can be observed. The anode potential should be recorded for reference in subsequent experiments. Currents can be drawn using the electronic load, ensuring the cell voltage does not drop below 50 mV to prevent damage. During operation, the purge valve should be opened every three minutes to prevent nitrogen and humidity accumulation in the anode compartment. If using the reference electrode, the purge process can be initiated based on an increase in anode potential, such as opening the valve if the anode potential rises by 60 mV from the start-up reference value.

3 Results

3.1 Most parts of a functional PEMFC can be built with easily accessible materials and instruments

A single OFC consists of two pressure plates, an anode (hydrogen) flowfield, a cathode (air) flowfield, an edge-reinforced Membrane Electrode Assembly (MEA), two flat gaskets, an anode inlet and outlet and - optionally - a DHE as reference electrode (Fig. 1). All components of the OFC can be fabricated using hobby grade CNC-milling machines as well as 3D-printers. Due to its modular and open design, the OFC can easily be adapted to the requirements of fuel cell research projects. In this case a DHE can be integrated into the MEA to determine the local electrochemical potential of the anode side. This allows for assessment of electrochemical correlations inside the PEMFC. To provide mechanical stabilization for the DHE, a ridge has been added to the anode end plate. Assembly of the operational OFC from individual components is straightforward and requires M3 screws and a torque wrench. For gas flow, push-in elbow fittings (SMC connectors) are installed as inlets in the anode endplate.

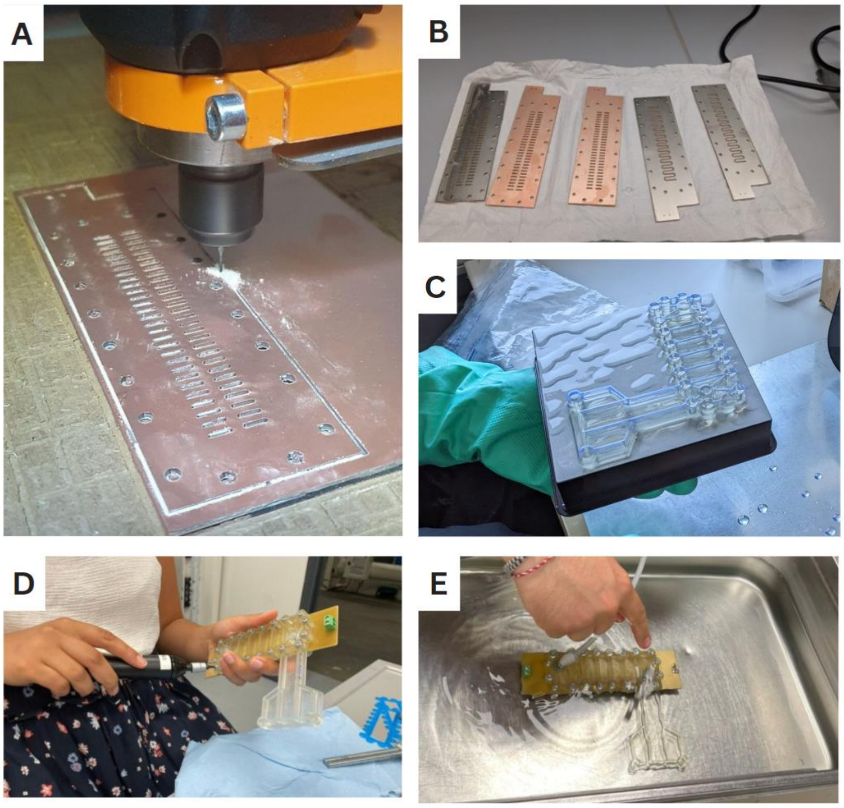

Fig. 3. (A) Milling of a cathode flowfield plate from printed circuit board material. (B) Three flowfield plates with nickel deposition after electroplating and two plates with copper surface without electroplating. (C) Anode pressure plate printed with VPP on a Formlabs Form 3+. (D) Assembly of an open fuel cell using a torque wrench. (E) Testing gas-tightness of an open fuel cell in a water bath.

3.2 During operation, the OFC resembles an industrial PEMFC in all main parameters

Despite its simplistic design, the OFC exhibits critical characteristics of an industrial PEMFC, making it an ideal tool for education and research projects. A particularly illustrative experiment involves determining the current-voltage curve (I-V curve) (Fig. 4). These experiments compare natural convection at the open cathode with forced convection achieved by blowing air over the cathode using a fan. The I-V curve reveals the three characteristic phases: activation overpotential, ohmic overpotential, and diffusion overpotential. Forced convection, which increases the air supply to the catalyst layer on the cathode, not only enhances the maximum current and electrical power output but also extends the linear I-V relationship within the region of ohmic overpotential (Fig. 4) [6].

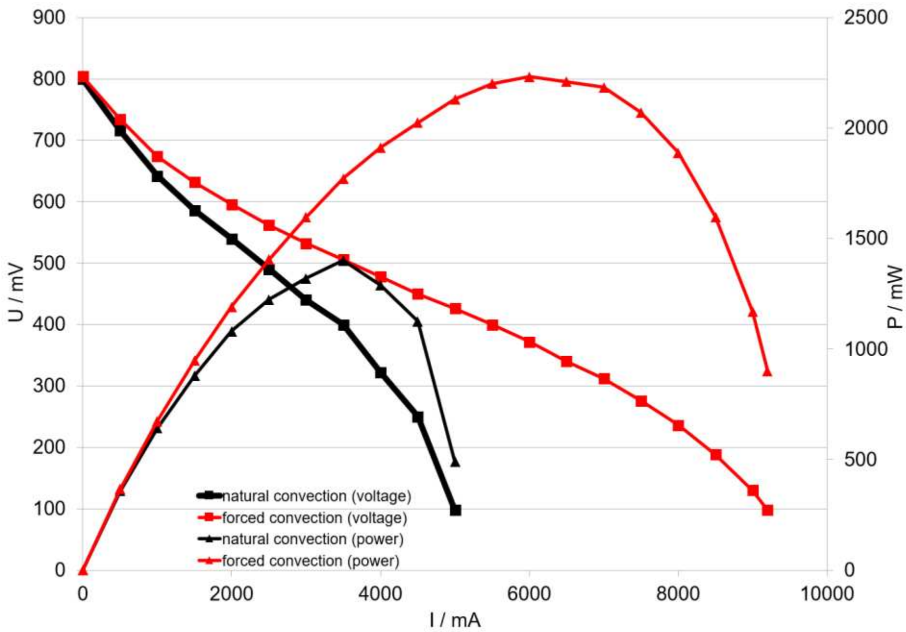

Fig. 4. Voltage and power dependence on the total current of the OFC under natural convection (black) and forced convection (red). Performance of the open fuel cell is substantially enhanced when subjected to increased air supply via forced convection.

An illustrative example of the electrochemical correlations within the PEMFC can be observed through the analysis of the cell voltage development and the electrochemical potentials at the anode over time. Upon initial hydrogen filling of the OFC anode compartment, an immediate drop of the measured electrochemical potential of the anode from 1200 mV down to 100 mV can be observed, followed by an immediate increase of the cell voltage to values of about 1100 mV (Fig. 5) resembling PEMFC behavior reported in the literature [6, 7]. Over the next few minutes, cell voltage decreases to roughly 900 mV. This equals the most common open cell voltage of a PEMFC during long term operation. After the initial drop, the electrochemical potential of the anode remains nearly constant. In line with the characteristic values of electrochemical current sources, the cell voltage equals the difference between the electrochemical potentials of the cathode and the anode. The potential of the anode remaining constant while the cell voltage decreases, indicates a decrease of the cathode potential. This decrease of the cathode potential might be caused by hydrogen diffusing from the anode towards the cathode leading to the formation of a mixed electrochemical potential at the cathode catalyst [8].

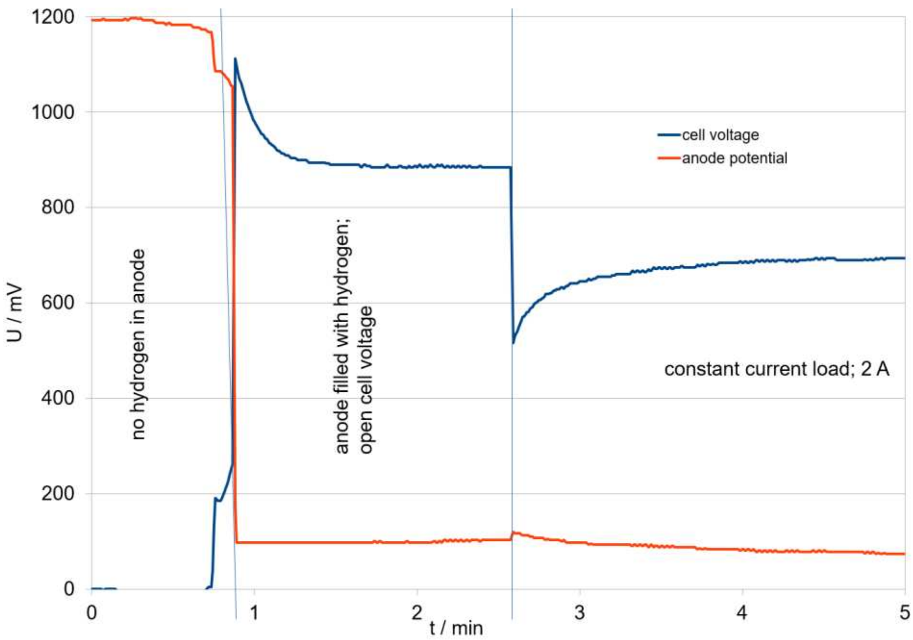

Fig. 5. Electrochemical performance of the open fuel cell. Anode potential (orange) and cell voltage (blue) over time upon initial hydrogen filling. Anode potential drops from 1200 mV to 100 mV upon initial hydrogen filling, while cell voltage rises to 1100 mV, then stabilizes at 900 mV. Applying a 2 A load decreases cell voltage to 500 mV, then gradually increasing to 700 mV.

Referring to the electrochemical potentials of the anode measured while the anode is filled with air and after flushing it with hydrogen, it can be concluded that the potential of the cathode is at least 1100 mV higher than that of the anode. These values come close to theoretical cell voltage to be 1230 mV under the given conditions [9]. Upon putting a constant current load of 2 A the cell voltage decreases to 500 mV which over the following minutes gradually increases up to 700 mV (Fig. 5). One significant aspect causing this initial voltage drop is the high resistance towards the proton conductivity of the initally dry membrane. The product water generated by the electrochemical reaction humidifies the membrane leading to better proton conductivity and therefore a lower voltage drop [10].

3.3 The OFC is an attractive system for both teaching and research on hydrogen technologies

The OFC project has been instrumental in teaching hydrogen technologies to students through various educational initiatives. In an advanced chemistry class at a secondary school in Muelheim, students engaged with the OFC. For this, a practical session on the OFC represented a conclusive hands-on experience complementing several teaching units on electrochemistry. The simplistic experimental setup, including a purge valve, electronic current load, and a hydrostick, allowed for experimental learning. A simple piece of cardboard was used to fan air into the open cathode, thereby demonstrating how improved air supply affected performance (Fig. 4). Similar demonstrations of OFC operation, including the importance of airflow in enhancing performance were given as part of University of Duisburg-Essen outreach events and at a Maker Day in Duisburg.

At a teacher conference in Mannheim, the OFC was demonstrated to educators, gathering valuable feedback for developing educational concepts. Students and participants conducted fundamental experiments, including determining I-V curve diagrams under natural and forced air convection, using hands-on, pencil-and-paper methods. These activities have the potential to propel fundamental understanding of fuel cell technology and showcase the OFC's simplicity and effectiveness in illustrating basic performance parameters of PEMFCs. These initiatives highlight the OFC's role in advancing science education by providing a practical, accessible tool to foster a deeper understanding of clean energy technology among students. Through these educational events, the OFC has proven to be a catalyst for inspiring the next generation of scientists and engineers.

4 Discussion

The OFC project aims to provide not only ready-made assembly kits and fully built OFCs but also to encourage a deeper exploration into the design and manufacturing of individual components. This initiative supports the use of various 3D-printing processes, such as MEX and VPP, which are commonly utilized in hobbyist or educational workshops. These methods require the processing of different materials, from hard plastics for endplates to elastic polymers for sealing elements. Despite the apparent simplicity of loading a 3D-model into a printer, each printing method presents specific advantages and challenges. Achieving the desired characteristics and precision necessitates familiarity with the printing technology and optimization of processing parameters for each material. Although this may seem laborious, it mirrors the challenges encountered in commercial fuel cell component production, making it an excellent training ground for students. The OFC kit uniquely addresses engineering and fabrication aspects, making it the first educational fuel cell designed with this comprehensive approach.

The OFC also offers significant benefits for examining electrochemical correlations within PEMFCs. For instance, students can analyze cell voltage and anode potential developments, which are influenced by the partial pressure of hydrogen and proton activity. Integration of a DHE provides a constant reference potential over time. In PEMFCs, the cell voltage results from the electrochemical potential difference between the cathode and the anode. Initially, filling the OFC's anode compartment with hydrogen replicates the theoretical voltage of around 1.2 V, which then stabilizes around 0.9 V as hydrogen diffuses through the membrane and reacts with oxygen at the cathode, creating a mixed potential.

Additionally, the OFC can demonstrate the importance of membrane humidity on fuel cell performance. During startup, the initially dry membrane exhibits high resistance to proton transport, leading to a significant voltage drop. As current is drawn and water is produced, the membrane humidifies, reducing resistance and voltage drop. Basic PEMFC characteristics can also be observed through I-V curves measured under natural and forced convection. These diagrams reveal phases of activation overpotential, ohmic overpotential, and diffusion overpotential. Forced air convection, demonstrated simply through the fanning produced by waving a piece of cardboard, can significantly enhance current output and power by improving oxygen transport to the cathode.

These experiments illustrate the practical application of PEMFC principles using the low-cost OFC in a minimalistic experimental environment. The OFC effectively demonstrates the significant electrochemical and operational characteristics of real-life PEMFCs, making it a valuable educational tool for exploring the development, production, and application challenges of fuel cells. This hands-on approach not only facilitates understanding but also encourages small-scale research projects, fostering the next generation of scientists and engineers in the field of clean energy technology.

In follow-up projects, which are currently in the conceptualization stage, we plan to manufacture 100 sets of OFC components to further lower the threshold for their use in schools, particularly those with limited technical resources. These kits could be distributed to teachers during a dedicated workshop, where participants will also receive specially designed training materials. Teachers will learn the assembly and application of the OFC directly from us, with each participant receiving two OFC kits. This initiative could further enhance the visibility of the OFC and advance the much-needed integration of hydrogen technologies into the school curriculum.

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References

1. Bezdek, R. H.: The Hydrogen Economy and Jobs of the Future. ECS Transactions 96(1), 107–120 (2020).
2. Smith, J. D., Novy, M.: Design of a Modern Proton-Exchange Membrane Fuel Cell Module for Engineering Education. 2018 IEEE Conference on Technologies for Sustainability (SusTech), pp. 1-6. IEEE, Long Beach, (2018).
3. Sendari, S., Wibawanto, S., Jasmine, J., Jiono, M., Puspitasari, P., Diantoro, M., Nur, H.: Robo-PEM educational kits to introduce fuel cell implementation for vocational high school with renewable energy major. AIP Conference Proceedings 2687, p. 040009, AIP Publishing, Melville NY (2023).
4. Zentrum für BrennstoffzellenTechnik gGmbH, Institut für Mikro- und Informationstechnik der Hahn-Schickard-Gesellschaft für angewandte Forschung e.V.: Schlussbericht vom 31.08.23 zu IGF-Vorhaben Nr. 53 EWN: Entwicklung von mit Mikrogasmesstechnik gekoppelten massenfertigungstauglichen Referenzelektroden zur Gewährleistung des sicheren Betriebs von PEM-Brennstoffzellen-Systemen. Institut für Umwelt & Energie, Technik &Analytik e.V.. https://www.iuta.de/igf/igf-forschungsprojekte/aif-nummer/53/ (2023), last accessed 2024/06/20.
5. The Open Fuel Cell Project, https://openfuelcell.org/, last accessed 2024/06/20.
6. Hinds, G., Brightman, E.: In situ mapping of electrode potential in a PEM fuel cell. Electrochemistry Communications 17, 26–29 (2012).
7. Dross, R., Maynard, B.: In-Situ Reference Electrode Testing for Cathode Carbon Corrosion. ECS Transactions 11(1), 1059–1068 (2007).
8. Zhang, Jianlu, Tang, Y., Song, C., Zhang, Jiujun, Wang, H.: PEM fuel cell open circuit voltage (OCV) in the temperature range of 23°C to 120°C. Journal of Power Sources 163(1), 532–537 (2006).
9. Kurzweil, P.: Brennstoffzellentechnik, Grundlagen, Komponenten, Systeme, Anwendungen mit 178 Tabellen. Studium und Praxis. Vieweg, Wiesbaden (2003).
10. Lee, Y., Kim, B., Kim, Y.: Effects of self-humidification on the dynamic behavior of polymer electrolyte fuel cells. International Journal of Hydrogen Energy 34(4), 1999–2007 (2009).
11. FreeCAD, https://www.freecad.org, last accessed 2024/06/20.