Electrochemical Compression

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- National Renewable Energy Laboratory, Golden, CO
- Rensselaer Polytechnic Institute, Troy, NY
- Gaia Energy Research Institute LLC, Arlington, VA

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Project End Date: June 30, 2020

Overall Objectives

Develop and demonstrate an electrochemical hydrogen compressor (EHC) to address critical needs of higher-durability compressors.

Fiscal Year (FY) 2018 Objectives

- Fabricate aromatic membranes with enhanced properties for use in EHCs; evaluate performance of aromatic membranes operating at 5,000 psi (350 bar).
- Improve EHC water and thermal management.
  - Develop water-management membranes (WaMM) for use in EHCs.
  - Engineer stack and cell components for high-pressure operation.
- Optimize stack hardware and demonstrate cell performance of ≤0.250 V/cell at current densities ≥1,000 mA/cm² at pressures of 5,000 psi (350 bar).

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan[1]:

(B) Reliability and Costs of Gaseous Hydrogen Compression.

Technical Targets

Table 1. Progress Toward Meeting Technical Targets for Hydrogen Compressors for Fueling Sites

Characteristics	Units	2020 Target[a]	2018 Giner ELX Status
Compressor Specific Energy	kWh/kg	1.62[b]	2.72[c] (<1.2)[d]
Uninstalled Cap. Cost[b]	$	170k	<450k
Outlet Pressure Capability	bar	950	350

[a] FCTO Multi-Year Research, Development, and Demonstration Plan, Hydrogen Delivery section.
[b] 100-bar delivery/commercial mechanical compressors are >6–8 kWh/kg (@7-bar delivery).
[c] Operation at 2-bar delivery.
[d] Projected at 100-bar delivery.

FY 2018 Accomplishments

Membrane Optimization:

- Reduced hydrogen back-diffusion in perfluorosulfonic acid (PFSA) membranes by >50%—applicable to aromatic membranes.
- Improved EHC efficiency—aromatic membrane: cell efficiencies to 2.7 $kWh_e/kg\text{-}H_2$ (@ 1,000 mA/cm²), 2-bar feed.
- Fabricated flexible WaMM compatible with high-pressure operation—significantly improves water management and cell voltage stability at high operating pressures.

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[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

Stack/System Hardware Development:

- Completed preliminary review of EHC system with Intertek (product testing and certification company).
- Established appropriated standards, component classifications, and operating requirements for certification.
- Initiated 875+ bar stack design and procurement of components.

INTRODUCTION

Hydrogen compression represents a key technical challenge for the widespread commercialization of fuel cell electric vehicles. To dispense hydrogen to fuel cell electric vehicles tanks, hydrogen must be compressed to a minimum of 875 bar. Conventional compressors account for more than half of the refueling station's cost and have insufficient reliability [1–3]. EHCs utilize direct current to electrochemically compress hydrogen to high pressures. Recent developments in membrane technology promise a new generation of very efficient, low-cost EHCs. The emergence of PEM-based solid-state EHCs eliminates many of the issues associated with mechanical compression; however, current state-of-the-art EHCs are challenged by issues related to membrane sealing and low operating current density attributed to poor water and heat management.

APPROACH

The work conducted in this program exploits the use of three novel technologies that include: (1) dimensionally stable aromatic membranes, engineered with low electro-osmotic drag and low hydrogen diffusivity, that exhibit high durability and sealing properties; (2) a WaMM that enables passive water feed and cell voltage stability; and (3) an advanced high-pressure stack design optimized for safe high-pressure gas compression. The aim of this project is to further develop and implement these technologies to improve water and thermal management within EHCs and enable high current density operation to reduce compressor cost.

RESULTS

Membrane Development

Perfluoroalkylsulfonate (BP-ArF4) and biphenylsulfonicacid polymers with 50% disulfone units (BPSH) were synthesized and cast into membranes with dimensions of 5.5" x 5.5". The strength of the membranes is enhanced via the addition of thermoplastic support structures. Membrane electrode assemblies (MEAs) were fabricated by bonding anode and cathode electrode structures to opposite sides of the membranes. The MEAs then were assembled into EHC stack hardware and individually tested. Evaluations initially were conducted using PFSA membranes to optimize the catalyst, flow-distributors (to improved heat and water management), and the WaMMs. The improvements then were incorporated into the EHC stack hardware design and used to evaluate and optimize the aromatic membranes developed during this program. Optimization studies were conducted at low pressure (280 psi). Select MEAs then were evaluated at pressures of up to 5,000 psi. (350 bar). In all tests, hydrogen was fed to the inlet of the EHC stack at a pressure of 35 psi (~2 bar) and electrochemically compressed to the final pressure. Utilizing this test methodology, an EHC cell voltage reduction of 0.6 V/cell (0.700 V/cell to 0.100 V/cell) at an operating current density of 1,000 mA/cm² was demonstrated at 280 psi (~20 bar) operation. Aromatic membranes, BP-ArF4 and BPSH, exhibited the best cell performance (lowest cell voltage) of 0.100 V/cell at an operating current density of 1,000 mA/cm² (Figure 1).

Following optimization studies at low operating pressures, aromatic membranes then were evaluated in EHC stack hardware rated for 5,200 psi (360 bar). Hydrogen was fed to the inlet of the EHC stack at a pressure of 35 psi (~2 bar) and electrochemically compressed to 5,000 psi (350 bar). Utilizing a back-pressure regulator attached to the outlet of the stack, hydrogen pressure was gradually increased while monitoring cell voltage at a constant current density of 1,000 mA/cm². During evaluation, MEAs fabricated with BP-ArF4 membranes exhibited a voltage of 0.217 V/cell at a current density of 1,000 mA/cm²: **The highest efficiency demonstrated by a single-stage EHC operating at 5,000 psi (350 bar)**. Under similar operating conditions, the cell voltage of a baseline PFSA membrane of similar thickness and ionic conductivity was measured at ~0.3 V/cell. Improvements in cell voltage of the aromatic membranes at high operating pressures are attributed to improved water management (high water content and lower electro-osmotic drag). In addition to improved cell voltage and efficiency, the aromatic membranes also demonstrated a significant reduction in hydrogen back-diffusion as compared to baseline PFSA membranes. The MEAs fabricated with BP-ArF4 membranes demonstrate a back-diffusion loss of 7% at an operating pressure of 5,000 psi (350 bar), compared to 27% when utilizing PFSA membranes (Figure 2).

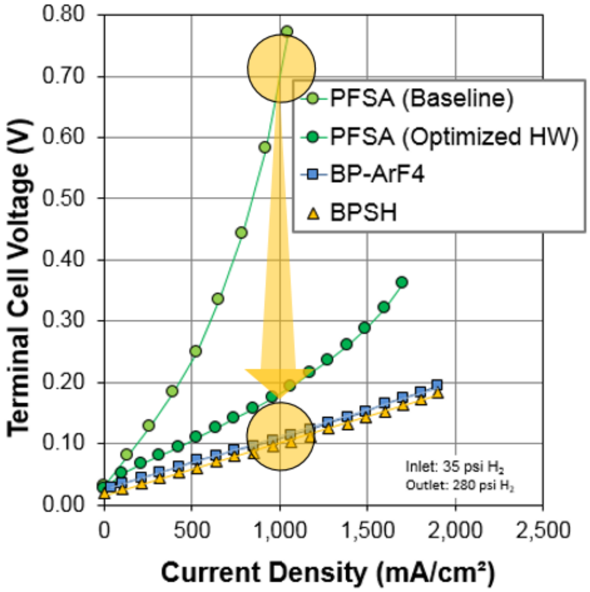

Figure 1. EHC cell optimization and performance at 280 psi (~20 bar)

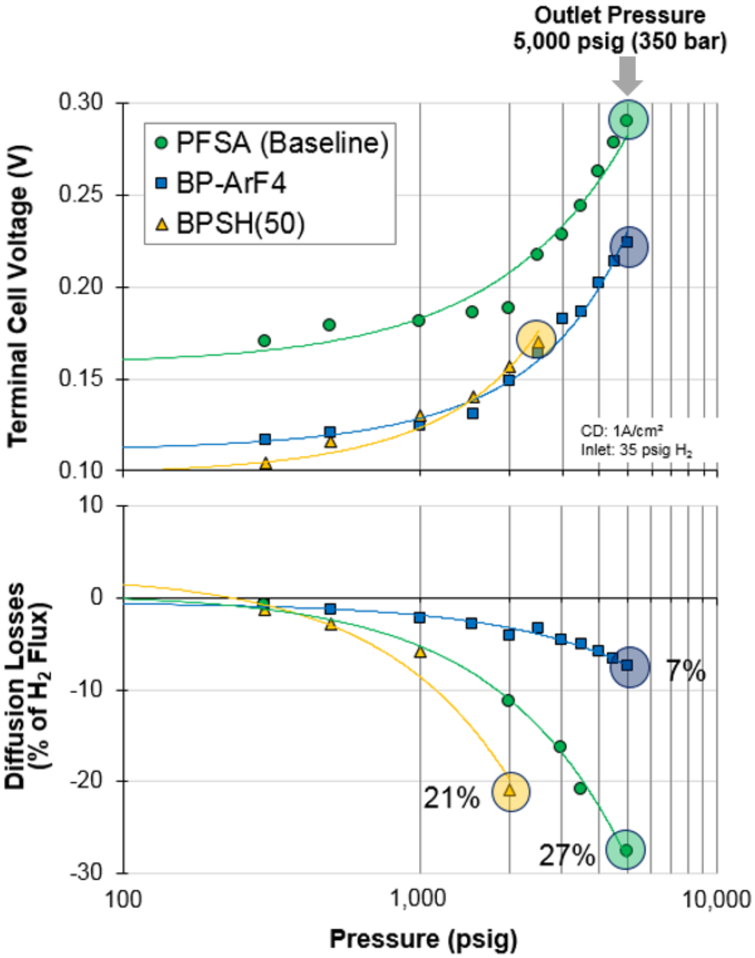

Figure 2. Performance of aromatic membranes at 5,000 psi (350 bar) operation

Separate testing demonstrated that hydrogen back-diffusion in PFSA membranes can be improved at elevated operating pressures. To illustrate this, membranes consisting of a mix of PFSA and synthesized polymers were evaluated in an operating EHC up to a pressure of 5,000 psi (350 bar). As shown in Figure 3, back-diffusion in the modified PFSA membranes was reduced by >50% as compared to "unmodified" PFSA. A trade-off between back-diffusion and cell voltage is realized depending on the amount and type of synthesized polymer. In one test, the modified-PFSA (Mod A) exhibited an improvement in cell voltage from ~0.300 V/cell to 0.240 V/cell at an operating current density of 1,000 mA/cm² and pressure of 5,000 psi (350 bar). Modifications that were implemented on PFSA membranes to reduce back-diffusion will be investigated on aromatic membranes under development in the upcoming year.

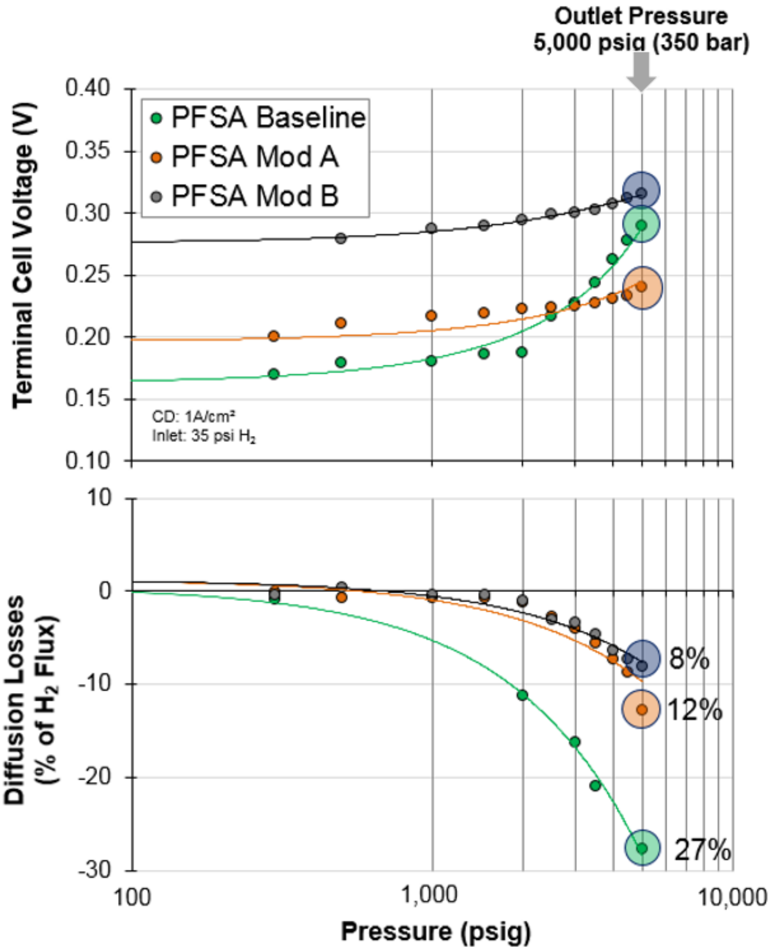

Figure 3. Performance of PFSA membranes at 5,000 psi (350 bar) operation

Electrochemical Hydrogen Compressor Stack Design

The mechanical challenge superimposed on the electrochemical design is the development of a cell-stack configuration that can tolerate high differential pressure across the membrane, cell components, and the outside environment. Giner has demonstrated differential pressures in excess of 5,000 psi (350 bar) using current stack technology. The ability to contain the overall pressure of the stack at an operating pressure of 875 bar requires the use of thicker end-plates to limit deflection, and an improvement in cell component strength.

A preliminary design of a scaled up (300 cm²) 875-bar stack design has been completed. Additionally, a 50 cm² version of the 300 cm² 875-bar stack design was machined, complete with all internal cell components.

Each of the 50 cm² 875-bar stack endplates (Figure 4) was designed to a thicknesses and diameter of 7 inches and 17 inches, respectively. As a comparison, the 50 cm² 350-bar hardware previously used to validate membrane performance at 5,000 psi (350 bar) has thicknesses and diameter of 4 inches and 12 inches, respectively. The 50 cm² 875-bar stack is currently undergoing proof pressure testing to 1,400 bar. The operational data (mechanical and electrochemical) obtained during stack evaluations will be used to validate the final design of the scaled-up 300 cm² 875-bar EHC stack. Issues related to sealing and cell performance can then be fine-tuned into the final scaled up design prior to fabrication.

Figure 4. 875 bar EHC stack (50 cm²)

Electrochemical Hydrogen Compressor System Design

This project requires the assembly of an EHC system, designed as a complete factory-packaged unit so that only minimal site preparation and installation work will be required. Operation will be completely automated, with a computerized control system providing load-following capability, safety interlocks, as well as remote control and monitoring. The EHC system will be pressure tested to the ASME standards, but special considerations will be taken into account for specialized fittings that will be certified to ANSI /HGV 4.10 (standard for fittings for compressed hydrogen gas and hydrogen rich mixtures).

A preliminary system piping and instrumentation diagram (separated into hazardous and non-hazardous zones), component selection, and layout have been initiated. With assistance from Intertek, a description of the applicable standards and codes required for certification were generated. Giner has initiated the procurement of equipment that will be used in the high-pressure operation of the stacks (for the testbed and system). The components are UL listed and rated for operation in classified hazardous areas zoned for Class 1, Division 2, Group B.

CONCLUSIONS AND UPCOMING ACTIVITIES

Significant progress has been made in the EHC membrane development. Giner and its team members have demonstrated membrane reproducibility and durability as well as a significant improvement in EHC cell efficiency. The progress made during this program has enabled EHC stack efficiencies in the range of 2.7 $kWh_e/kg\text{-}H_2$ (flux). Additionally, development efforts conducted under this project have resulted in cost reductions of PEM-based EHC stacks and systems. Future plans include the following.

- Membrane: Complete investigation on aromatic membranes.
    - Continue optimization to reduce back-diffusion in aromatic membranes.
    - Scale up aromatic membranes from 50 cm^2 to 300 cm^2.
- Stack: Fabricate and test high-pressure 12,688 psi (875 bar) stack hardware.
    - Initiate 875+ bar testing in 50 cm^2 hardware, then in 300 cm^2 hardware.
- System: Initiate assembly of prototype system design.
    - Complete preliminary design of lab-scale prototype unit (piping and instrumentation diagram, process flow diagram, electrical, layout, hazard and operability study).
    - Complete selection and procurement of system components.
    - Review and certify EHC design with third-party nationally recognized testing laboratory (Intertek).

FY 2018 PUBLICATIONS/PRESENTATIONS

1. W. Colella and M. Hamdan, “Energy Systems, Thermodynamic, and Financial Analysis of Low Temperature, Proton-Conducting Electrochemical Hydrogen Compressors (EHCs) for Distributed Energy Storage,” 233rd ECS Meeting, May 13–17, 2018.
2. M. Hamdan, “Advanced Electrochemical Hydrogen Compression,” 2018 International Hydrogen Infrastructure Workshop, Presentation, September 11–12, 2018.
3. M. Hamdan, “Advanced Electrochemical Hydrogen Compressor,” 234th ECS and SMEQ Joint International Meeting, October 2, 2018.
4. M. Hamdan, “Electrochemical Compression,” 2018 Hydrogen Annual Program Merit Review Meeting, Presentation PD136, June 14, 2018.

REFERENCES

1. Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan: Hydrogen Delivery. http://energy.gov/sites/prod/files/2015/06/f22/fcto_myrdd_delivery.pdf.
2. G. Parks et al., Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs (NREL Independent Review, May 2014).
3. “Hydrogen Fueling Infrastructure Analysis.” National Renewable Energy Laboratory. https://www.nrel.gov/hydrogen/hydrogen-infrastructure-analysis.html.