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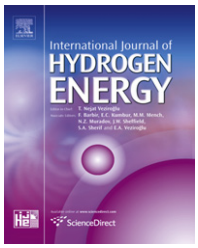

News and Views

International hydrogen association for hydrogen energy design competition applied topic A: Portable fuel cell

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ABSTRACT

The Penn State chapter of the International Association for Hydrogen Energy supplied a team of 12 members to enter the 1st IAHE Hydrogen Design Competition. Our design team decided to build a portable fuel cell. The design objective was to limit the cell size to 6 cm × 6 cm × 2 cm, and the goal was to achieve maximum power over 1 h of operation. The type of fuel cell we chose was a proton exchange membrane (PEM) fuel cell, using hydrogen and oxygen as the fuel and oxidizer, respectively. The final design converged to a cell stack containing 6 bipolar/end plates, i.e. 5 cells, each measuring 6 cm × 6 cm × 1.975 cm, each with an active area of approximately 25 cm^2. The total open circuit voltage was approximately 4.75 V, indicating an average 0.95 V per cell. With an active area of 25 cm^2, the maximum power observed during operation was approximately 1.7 W cm^{-2}. The maximum sustained power over 1 h averaged 1.15 W cm^{-2}. The total cost of the project totaled $2245.

1. Introduction

Fuel cell technologies have been a proven clean and efficient way of generating electricity for over a hundred years. Currently, there is a growing need for small, portable power supplies for electronic devices. Everything from laptops to kitchen supplies need to be powered, and small portable fuel cells may be the best alternative energy device for certain applications due to their high power density and efficiency. The International Association for Hydrogen Energy (IAHE) established the 1st IAHE Hydrogen Design Competition, in which the challenge was to produce a portable fuel cell with the cell dimensions no larger than 6 cm × 6 cm × 2 cm. Out of over 50 members, 10 decided to participate on the PSU IAHE Design Team. The design team worked for six months designing, manufacturing and testing their fuel cell. This report will provide the background of the team, an overview of the innovative design, and the performance data.

2. Background Information

2.1. International Association of hydrogen energy PSU chapter

The Pennsylvania State University chapter of IAHE was created in the spring of 2009. Its first meeting was held on March 26, 2009. Currently, the PSU chapter has over 50

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members and is engaged in 2009/2010 IAHE design competition. President Abdulkader (AK) Srouji and Vice President Michael Manahan lead the chapter, which supports a number of student activities and hosts guest speakers. The chapter provides a promising future for students entering into the field of hydrogen energy research (Fig. 1).

2.2. *Penn State hydrogen research*

Penn State is at the forefront of the transition to a hydrogen based economy. Numerous professors are extensively involved in the capabilities of hydrogen as a fuel source. Dr. Martin Klanchar (ARL) is researching undersea propulsion, Dr. Joel Anstrom (PA Transportation Institute) is involved in hybrid and hydrogen vehicles, and Dr. Chunshan Song is looking into the production of hydrogen from other renewable resources. Penn State is the home for the H_2 Energy Center which has a multi-faceted approach to hydrogen-related research. The IAHE faculty advisor, Professor Matthew Mench, is founder and director of the Fuel Cell Dynamics and Diagnostics Laboratory, which investigates multi-phase transport phenomena in hydrogen fuel cells.

Furthermore, one of the few hydrogen fueling stations in Pennsylvania is located at Penn State. The station provides a hydrogen/natural gas mixture as fuel for two cars, a bus and several vans that travel throughout University Park. An electric car that was donated by General Motors and has been modified to run on pure hydrogen also uses this station.

2.3. *Goals and objectives*

In preparation for the 1st IAHE Hydrogen Design Competition, the IAHE design team developed goals and objectives to achieve during our design process. As a team comprised of graduate and undergraduate students, as well as those with and without fuel cell background, the team wanted to:

Fig. 1 – The 2009–2010 PSU IAHE Fuel Cell Competition Team. Front row, left to right: Nathan Chidiac, Samantha Atmur, Kamiar Salehi, Benjamin Goldberger, Marta Hatzell, Nathan Peck, AK Srouji; Back row: Michael Manahan, Sean Doutt, Jason Clark, Matthew Browe.

- Network as a team through weekly meetings
- Increase our knowledge of fuel cells
- Design a fuel cell with the highest useful output over an hour of operation
- Build contacts within the fuel cell industry
- Make a contribution to push fuel cells closer to their widespread market penetration

Each of these goals was realized through the duration of the project.

3. Results and discussion

The PSU IAHE cell design team encountered unexpected experimental difficulties. Due to the higher voltage and higher current operating conditions, many of the experimental test stations that the laboratory is typically equipped with were rendered unusable. This equipment typically tests single cells, on the order of up to 250 cm^2 at less than 1.0 V open circuit potential (OCP). This stack had an OCP of approximately 4.5 V, indicating approximately 0.9 V per cell, which is typical of the academic cells run in our laboratory. Our cell, with approximately 25 cm^2 of active area per cell, should produce much higher current. For example, at an operating condition of 1 A cm^{-2}, our cell should produce approximately 25 A. For higher current densities, we could see up to 50–60 A. Therefore, attention was given to wire selection, machine capacity, and heat generation inside the cell.

Because of these limitations, only the stack capable test equipment in the lab was available. Unfortunately, upon beginning a break-in cycle, the humidifier system would not supply the cathode gas stream above approximately 1.3 slpm, despite its rating for up to 20 slpm. After analyzing the system, it was clear that the humidifier bottle was the limiting factor that restricted the higher flow of air. With a short time constraint and no other humidifiers capable of humidifying higher flow rates, the team decided to proceed with the break-in procedure, however to use pure oxygen in the cathode stream, as opposed to more readily available air. This effectively increased the stoichiometry from less than one (with air) to around 2.3 (with pure oxygen). We recognize, therefore, that the testing conditions are different than that which we intended, and the reported data were not obtained at the “normal” conditions.

As a result of the modified system described above, we should qualitatively discuss how water management, a key factor in fuel cell performance, is affected. First, the flow rates are significantly affected. While the stoichiometry of the system is around 2.3, the flow rate of the gas through the cell is significantly lower. Therefore, the water removal rate by evaporation and drag is much lower with pure oxygen than it would be with an air system. With this size cell, and without a thermal management system, water management becomes increasingly important. One very low cost, low parasitic-loss method that can be employed to enhance the water removal is through the use of a periodic purge or pressure pulse. This can aid in slug and other water removal, and quickly boost system performance. Throughout several of our tests, we experimented with this method, and found it to be very useful especially under high current conditions.

3.1. System calculations

3.1.1. Consumption of reactant gases

Molar consumption rate of reactant gases

$$\dot{n}_x = \frac{1}{y_x}\frac{iA}{nF}\lambda\, n_{cells} \tag{1}$$

While testing the PSU IAHE cell, the anode and cathode were run at a constant flow rate stoichiometry of 3.2 and 2.7 respectively (stoichiometry at 1 A/cm^2). In actual operation, we would anticipate the stoichiometry of the anode to be 1, as the cell would rely on the hydrogen consumption (hydrogen flow dead-ended). This design eliminates the need for a hydrogen recirculation system. On the contrary, it does complicate the water management at the anode since water is not readily removed. Therefore, it is suggested that a systematic purge system be installed at the anode in order to purge at specified times to remove excess water that prevents optimal performance. Other values needed to perform flow rate calculations are summarized in Table 1.

Therefore, Equation (1) for the anode at 1 A cm^{-2} becomes:

Molar flow rate for the anode at 1 A cm^{-2} at a stoichiometry of 3.2

$$\dot{n}_{H_2} = \frac{1(1\ \mathrm{A\,cm^{-2}})(24.75\ \mathrm{cm^2})}{1\ (2e^-)(96485c/\mathrm{eq}-\mathrm{e}^-)}(3.2)(5) = 0.002052\ \mathrm{mol}H_2/s \tag{2}$$

And for the cathode at 1 A cm^{-2}:

Molar flow rate for the cathode at 1 A cm^{-2} at a stoichiometry of 2.7

$$\dot{n}_{O_2} = \frac{1(1\ \mathrm{A\,cm^{-2}})(24.75\mathrm{cm^2})}{1\ (4e^-)(96485c/eq-e^-)}(2.7)(5) = 0.000866\,\mathrm{mol}O_2/s \tag{3}$$

3.1.2. Total System Volume

Total System Volume

$$V_{system} = V_{cell} + V_{H_2\,Tank} + V_{Air\ Tank} \tag{4}$$

Total System Volume for Chosen Experiment Test Conditions

$$V_{system} = \left[6\ \mathrm{cm} \times 6\ \mathrm{cm} \times 2\ \mathrm{cm} \times \left(\frac{1\ \mathrm{m}}{100\ \mathrm{cm}}\right)^3\right] + \left[0.002052\frac{\mathrm{mol\ H_2}}{\mathrm{s}} \times 0.0224\frac{\mathrm{m^3}}{\mathrm{mol\ H_2}} \times 3600\ \mathrm{s}\right] + \left[0.000866\frac{\mathrm{mol\ air}}{\mathrm{s}} \times 0.0000225\frac{\mathrm{m^3}}{\mathrm{mol\ air}} \times 3600\ \mathrm{s}\right] = 0.166\ \mathrm{m^3} \tag{5}$$

Table 1 – A list of operating parameters.

Parameter	Value
y_{anode}	1 (pure hydrogen)
$y_{cathode}$	1 (pure oxygen)
A	24.75 cm^2
n_{cells}	5
$n_{hydrogen}$	2 electrons
n_{oxygen}	4 electrons
F	96485 C/eq e$^-$
λ_{anode}	3.2
$\lambda_{cathode}$	2.7

3.1.3. Tank sizing

It has been assumed that the air and hydrogen will be supplied at a pressure of 10 000 psi (approx. 70 MPa), which is currently a high- technology tank design. Several years from now, when a fuel cell similar to ours would be released, this type of tank will likely be a standard component (Table 2).

Hydrogen tank volume

$$V_{H_2\ Tank} = \frac{n_{H_2}R_uT}{P} = \frac{\dot{n}_{H_2} \times 3600R_uT}{P} = \frac{0.002052 \times 3600 \times 8.314 \times 293}{68,950,000} = 0.26\ \mathrm{L} \tag{6}$$

Oxygen tank volume

$$V_{O_2\ Tank} = \frac{n_{O_2}R_uT}{P} = \frac{\dot{n}_{O_2} \times 3600R_uT}{P} = \frac{0.000866 \times 3600 \times 8.314 \times 293}{68,950,000} = 0.11\ \mathrm{L} \tag{7}$$

3.1.4. System Gravimetric density

Estimated Gravimetric Density

$$\text{Gravimetric density} = \frac{28.8(\text{watts}) \times 3600(\text{s})}{0.072(\text{L})} = 1.44\ \mathrm{MJ/L} \tag{8}$$

3.1.5. Fuel Cell Efficiency

The overall thermodynamic efficiency of the fuel cell can be easily calculated:

$$\eta_{th} = \frac{\text{actual electrical work}}{\text{maximum available work}}$$

The average electrical energy obtained over the 1 h period was 1.15 Wh cm^{-2}.

At approximately 60 °C (the cell naturally heated to this value), the thermal voltage (maximum available work) can be described as,

Thermal Voltage Calculation

$$E^{oo}(333K) = -\frac{\Delta H}{nF} \times n_{cells} = -\frac{-242170}{(2)(96485)} = 6.25\ \mathrm{V\ \ per\ cell} \tag{9}$$

At 9 A (the steady operating condition), for 1 h, this equates to 56.25 Wh. Therefore,

Cell Efficiency

$$\eta_{th} = \frac{28.8}{56.25} = 51.0\% \tag{10}$$

3.1.6. System efficiency

During the experiments, we ran two pieces of ancillary equipment. First, a small fan was used to aid in convective heat transfer. We estimate that the flow rate was comparable to a computer fan, which can be powered for 1.5 W, or 1.5 Wh. The second piece was the humidification system. Originally, we designed the system to run off of dry gases. However, upon

Table 2 – Variables required to determine tank sizing.

Parameter	Value
P	70 MPa
R_u	8.314 m^3 Pa/K mol
T	294 K

testing, we saw a sharp increase in the membrane resistance, leading to poor performance, when dry gases were applied. The humidification system that was employed was oversized for this application. Therefore, below is an estimation of the energy required to create an equivalent 100% relative humidity at approximately 60 °C.

Undergoing a basic calculation, we can estimate the power required to supply fully humidified gases at 60 °C:

Power requirements for humidification

$$\dot{Q} = \dot{m} c_p \Delta T \tag{11}$$

Where $\dot{m}$ is the mass flow rate of the water vapor entering the cell. This can be calculated based on the pressure, saturation pressure, stoichiometry, and the relative humidity. After calculating,

$$\dot{Q} = 4.33 \times 10^{-6} \mathrm{kg/s} * 1.89 \mathrm{kJ/kg} \times K * 35K = 28.6 \mathrm{W}$$

For 1 h, this is 28.6 Wh.

Therefore, for the complete system, there is a negative net efficiency. While we did not optimize the humidification levels, alternative approaches should be considered, such as recirculation of the exhaust humidity for self humidification, dead-ending the anode side to maintain higher humidity, or optimizing the required inlet humidity to achieve a balance between humidifier power requirements and cell performance.

4. Testing results

After hydrating the stack and conditioning each cell membrane, a polarization curve was extracted in order to have a preliminary evaluation of performance and cell behavior. A polarization curve is often used to determine a) current density for which the stack experiences flooding leading to loss of performance, b) the operating conditions of peak power generation by the stack, and c) the optimal operating parameters. The polarization curve was measured by running the cell in galvanostatic mode. Each point is the average of 5 min at a given current. The polarization curve and power curve are shown in Fig. 2 below.

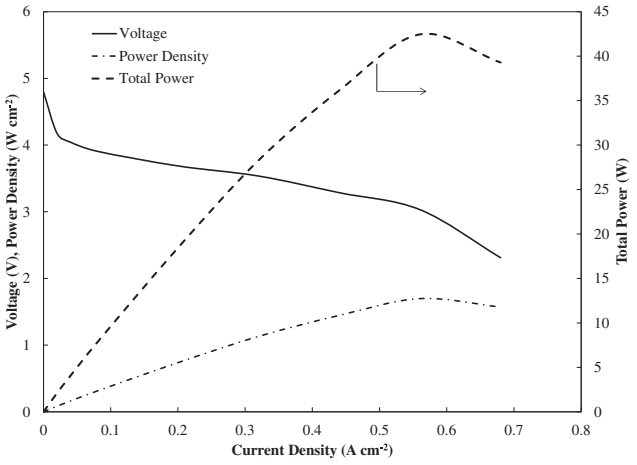

Fig. 2 – Stack performance curves showing voltage, power density and total power versus current density.

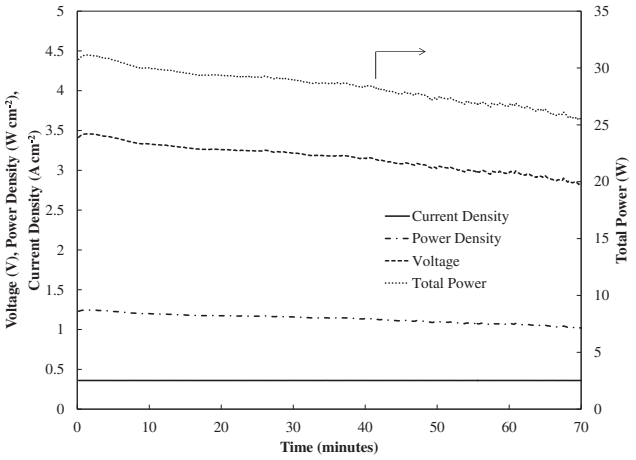

Fig. 3 – One-hour operation at 9 A (0.36 A cm^{-2}), showing voltage and power degradation.

Although maximum power is reached at 42 W, the stack behaved with too much instability and suffered from flooding. We can also see a dip on the performance curve at 14 A, which evidences flooding at much lower current densities than typically seen in academic cells. Typically, flooding behavior is not seen until 1.5 A/cm^2. The change in slope at 14 A indicates that there is a water management issue interrupting the ohmic region. In order to choose an operating point for the greatest sustained power, the team had to ensure stability over 1 h operation. Constant current operation at 9 A was recorded for an hour and is shown in Fig. 3.

For a 1 h operation at a constant current of 9 A, the rated power is relatively steady with a degradation from 31 to 28 W. It is believed that water accumulation in the channels, diffusion media, and/or manifold area is responsible for this 9.6% degradation.

A qualitative analysis of non-ohmic losses can be achieved through electrochemical impedance spectroscopy (EIS). This technique would help determine the exact operating conditions where mass transport resistance becomes dominant. This level of evaluation is out of the scope of this project.

Cyclic voltammetry is another useful tool that can be used to determine electrochemical surface area (ECSA) of each cell

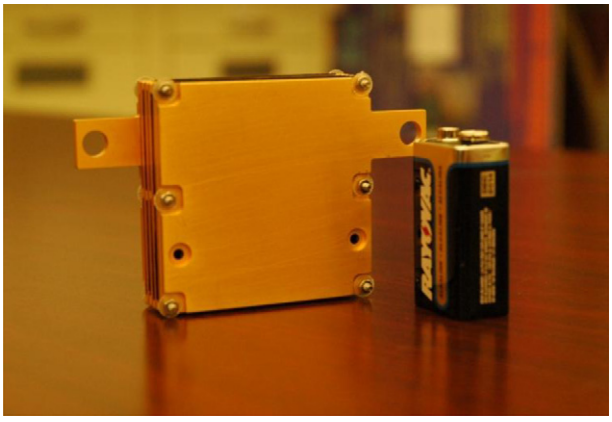

Fig. 4 – PSU IAHE assembled cell next to a 9 V battery for size comparison.

Table 3 – Development Costs.

	Quantity	Price per Unit ($)	Total ($)
Corrosion-Resistant Aluminum (alloy 5052), 0.125'' thick, 24"x24"	1	29.45	29.45
Gas Diffusion Media SIGRACET© 25 BC with PTFE	2	60	120
High-Temperature Insulating Polyimide Flat Washer, No. 2 Screw Size, .25" OD, .004"-.006" Thick, Packs of 10	2	5.41	10.82
Insulating Fiberglass Flat Washer, No.2 Screw Size, .25" OD, .01"-.02" Thick, Packs of 10	2	2.57	5.14
Low-Friction PTFE Flat Washer, No. 2 Screw Size, .25" OD, .01"-.02" Thick, Packs of 10	1	2.45	2.45
Metric Cheese Head Slotted Machine Screw, 18-8 Stainless Steel, M2 Size, 20 mm Length, .4 mm Pitch, Packs of 100	1	6.63	6.63
Metric 18-8 Stainless Steel Thin Hex Nut, M2 Size, .4 mm Pitch, 4 mm Width, 1.2 mm Height, packs of 50	1	3.82	3.82
Color-coded Aluminum Shim Stock, .15" Thick, 6"'cross' 24"	1	6.39	6.39
Membrane Material	1	820	820
Gold Plating	1	553	553
Machining Costs	55 h	12.50	687.50
Total Cost of Cell (USD)			2245.20

in the stack. Any discrepancy in ECSA from one cell to another could be indicative of a limiting cell in the stack. Also comparison of ECSA between two periods of time can indicate degradation on the catalyst surface. Again, this type of analysis was out of the scope of the project.

As a final result, the PSU IAHE team wanted to include a photograph of their completed, assembled cell. It is shown in Fig. 4.

5. Budget summary

The cost associated with developing and building the fuel cell is broken down into two areas, materials and manufacturing. A table summarizing all costs is shown in Table 3. Overall, the development cost for this project was $2245.20. Primary funding for this project came from the Penn State University Park's allocation committee (UPAC).

5.1. *Materials*

Due to the flow field design, manufacturability, and low cost, aluminum was chosen as the material for the bipolar plates. Each cell has SIGRACET® 25BC gas diffusion layers (with micro-porous layer) to minimize cell thickness while provide good electrical and thermal contact with the catalyst layer. A Gore membrane was used.

5.2. *Manufacturing*

All cell manufacturing took place within Penn State's Mechanical Engineering machine shop. The total time to manufacture the cell was approximately 55 h, which includes machining and the time to create the machining code. The cell was machined with an air spindle at 40 000 rpm. This air spindle was used in order to achieve higher dimensional accuracy and decrease machining time in comparison with a conventional spindle. In addition to the machining of the cell, Penn State sent the cell to Klein Plating Works, Inc. (Erie, PA) to be nickel and gold plated to prevent aluminum oxidation during operation. The base nickel coating was 500 microinches thick, and the outer gold plating was 100 microinches thick. The plating cost approximately $600.

6. Conclusion

In the coming years, fuel cells will play an important role in reducing the amount of power used by small electronic devices. Through this project, Penn State's IAHE group was able to design, build, and test a 72 cm^3 fuel cell stack and received a rather unsteady maximum power output of 42 W. The cell was operated for 1 h at 28.5 W with complete stability. Future design iterations of this cell will include: 1) gas inlet design, 2) manifold design. While obvious improvement to the stack design may include different flow field dimensions, change in plate compression, and periodical pulse purge; the overall performance obtained validated the technologies' usefulness, and was an invaluable learning experience for the entire team. The team would also like to direct readers to a Youtube video located at http://www.youtube.com/watch?v=Qk2HVWLqJHw.

Acknowledgments

The PSU IAHE design team would like to thank Professor Matthew Mench, our chapter's faculty advisor, for his input and the use of the equipment in his laboratory. We also want to thank Phil Irwin, the PSU Mechanical and Nuclear Engineering Department machinist, for his dedication in machining our parts in a short amount of time. Finally, we want to thank the University Park Allocation Committee for funding the majority of this project.