Design and Implementation of a Fuel Cell Laboratory Experience for Freshman Engineering Students

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The Department of Engineering Education (ENGE) at Virginia Tech conducts several hands-on exercises in the Frith Freshman Design Laboratory throughout the academic year. A recent addition to this design laboratory experience is a laboratory on fuel cells. This laboratory experience focuses on the operation and applications of fuel cells as a power source and allows the students to handle and operate their own bench-scale prototype fuel cell. During a 50-minute visit to the Frith Lab, students are guided through a brief background lecture before teams of two each receive a proton exchange membrane fuel cell (PEMFC) on which to conduct their own experiments to investigate this important and emerging technology.

The PEMFC apparatus is powered by hydrogen that is produced in the laboratory via solar-powered electrolysis of water where the *solar energy* is provided by a sun lamp. This experimental setup allows demonstration of the entire green energy cycle to the students. Load boxes are used to perform measurements that are more detailed and generate the characteristic fuel cell voltage curves.

Exposing engineering students to emerging technologies is one way of keeping them interested and engaged in their education, especially when the experience is a hands-on activity. This fuel cell exercise offers students the opportunity to handle and operate their own small fuel cell unit and offers a means to educate virtually every first year engineering student on an important alternative energy source. In this paper, the details of funding, budget, equipment and implementation will be fully described.

INTRODUCTION

The importance of active learning (hands-on) experiences as a part of the engineering undergraduate education experience is well established. The challenge for today's educators is to design active learning experiences for students that fit within the curriculum framework and are logistically and economically feasible[1,2]. The proton exchange membrane fuel cell (PEMFC) lab described herein is a hands-on laboratory experience that incorporates emerging technology into a useful and interesting activity that may be used as is or modified to suit specific needs/circumstances. The PEMFC lab is intended for freshman engineering students, but can easily be adapted to other educational circumstances.

Virginia Tech has used the Frith Freshman Design Laboratory as a venue for many active learning experiences designed to stimulate the interests of first-year engineering students.

The freshman program includes several mandatory Frith Lab activities that usually involve some aspect of active learning such as reverse engineering, precision measurements, gear ratios, etc. These activities are integrated into the second semester of the first-year engineering curriculum.

This PEMFC lab was initiated in spring 2004 using funds donated by the Virginia Tech Student Engineering Council (SEC). The donation was used to purchase twenty small, dissmantalable PEM fuel cells specifically intended for educational purposes. The initial lab activity involved discussing aspects of fuel cell technology such as the history of fuel cells, hydrogen storage issues and fuel cell applications. Student participation included running a small motor powered by a fuel cell and taking open circuit voltage measurements to calculate fuel cell efficiency. Virtually 100% of students had never seen a fuel cell and all were intrigued by this emerging technology. Due to the popularity of the PEMFC lab, it was decided that this lab activity should be expanded the following year.

Additional funds contributed by the SEC during spring 2004 allowed expansion of this lab into the more comprehensive, green energy cycle, fuel cell lab described herein. Electrolysers, UV lamps, solar collection modules, and hydrogen generation/storage units were purchased to demonstrate energy generation from solar power to usable energy. Load measurement boxes were purchased to allow students to take current and voltage measurements simultaneously. Most of these components are readily available on-line from *Fuelcellstore.com*

The PEMFC Laboratory

The Virginia Tech first-year engineering program is administered by the Department of Engineering Education (ENGE). All first-year engineering students enter the College of Engineering as general engineering majors and must successfully complete the GE program prior to admission into a degree-granting program. A second semester course focuses on engineering design and this theme is emphasized in the PEMFC laboratory through a focus on power source choices, various fuel cell classifications, fuel cell characteristics/properties, and real-world fuel cell applications.

Students are given a brief introduction to fuel cells in lecture, prior to any work in the lab. A worksheet (attachment) is provided that contains basic information specific to the fuel cells to be used, safety precautions and a set of pre-lab questions/calculations. The pre-lab questions are due prior to the start of lab work. Students are also referred to specific internet sources for additional information if they wish to investigate further. Two excellent web sources on fuel cells[3,4] are:

- Smithsonian Fuel Cell Project. A very good overview of all fuel cell types written so that anyone may understand without prior knowledge on the subject. (http://www.americanhistory.si.edu/csr/fuelcells/basics.htm)
- Ballard Inc. This site contains an excellent video clip on the use of PEMFC units for transportation applications. (http://www.ballard.com/)

All of the data necessary to complete the PEMFC lab and follow-up questions must be collected within the 50 minute class time, so it is important that students arrive ready to begin. The pre-lab assignment, collected at the start of lab, is designed to assure that students arrive with the requisite background knowledge to begin the lab procedure. The pre-lab contains a description of the apparatus to be used, safety information, and several basic calculations. Students are expected to have no prior exposure to electric circuits, so some questions are intended as practice for the characteristic fuel cell curve generation and efficiency calculations; however, the required knowledge of circuitry is minimal.

The logistics of running the PEMFC lab as described are relatively simple if adequate preparation is done beforehand. Hydrogen generation and storage is the most problematic issue in the lab, just as in real-world applications. Several options for hydrogen are available to educators and the optimal solution will depend upon each situation. The three most viable options for hydrogen generation and storage are:

- Compressed hydrogen may be purchased directly from a supplier, and then used to fill individual H_2 storage units used by each group. This method is relatively inexpensive and simple to implement, however the true costs associated with hydrogen production and storage are less apparent to the students.
- Hydrogen may be generated by using $BaCo_3$ and distilled water. Catalysts for generation of hydrogen via this method may be purchased from the supplier and the $BaCo_3$ may be purchased from most chemical suppliers. This method is simple, though the $BaCo_3$ compound is expensive.
- Hydrogen may be generated via electrolysis of deionized water. UV lamps and solar panels can be used to power electrolysers, which in turn generate hydrogen from water. This method is recommended because it demonstrates that a simple, cost-effective means of energy storage and electricity generation may be employed wherever sunshine and water are available.

Purchased hydrogen was used in the first iteration of this lab because it was readily available and funding for additional equipment had not yet been secured. Hydrogen generation using solar-powered electrolysers is currently employed and this adds a new and interesting dimension to the student's experience.

The lab activities may be conducted in groups of two to four students. The students must make their own data tables and enter the data into their design notebooks. We have focused on having the students use the data to generate the characteristic curve for their PEMFC and calculate the Faraday and energy efficiencies. Detailed explanations of these parameters are readily found in basic texts on the subject[5]. Simply put, the characteristic curve describes the voltage obtainable from a PEMFC as it varies with the current (amperage) in the circuit. Faraday efficiency is the ratio of actual versus theoretical volume of hydrogen required to produce a certain voltage and current. Energy efficiency is the ratio of electrical energy produced by the fuel cell to the latent energy of the hydrogen used.

Data collection in the lab, as we have implemented it, consists of two parts: data for the characteristic curve and data for the efficiency calculations. Students take measurements from a fuel cell powered circuit by recording current and voltage values at varying levels of resistance. Load measurement boxes purchased are equipped with a variable resistance feature and allow this step to be completed simply by turning a knob to select the value of resistance and recording the measured current and voltage. Students generate the characteristic curve by plotting values of voltage versus current for each level of resistance. A power curve can then be generated by calculating electrical power at each resistance level and plotting power versus current data pairs.

Students take the required measurements for the efficiency calculations by recording the volume of hydrogen consumed by the PEMFC to produce a constant current and voltage over a fixed time. Efficiency values will vary depending on the resistance level at which students choose to perform this step, and students are asked in the post-lab exercise to explain this phenomenon.

It is important that an appropriate instrument be used for current and voltage measurements as the characteristics of the measuring instrument can alter the circuit and result in error due to the low voltage of the PEMFC. The on-line vendor fuelcellstore.com sells load boxes specifically for this application, though they are somewhat expensive. Many other possible experiments and measurement techniques using the apparatus may be found in the literature, on the internet, and from the supplier[6,7] .

Laboratory Implementation

The initial set up consisted of 20 take-apart PEMFC units purchased from fuelcellstore.com (manufactured by heliocentris) using a $2,500 grant from the SEC. These units were used in conjunction with compressed hydrogen and were very successful during the first year. Approximately 1,000 first-year engineering students performed the PEMFC lab; fewer than 10 of these students had ever seen a fuel cell before.

The SEC granted an additional $4,000 for expansion and improvement of the lab based upon the positive response to the first lab exercise. This money was used to purchase hydrogen storage cylinders, electrolysers, solar collection modules, UV lamps, load measurement boxes, and other accessories such as tubing and cables.

The authors designed the lab procedure, pre-lab and post-lab exercises, and a PowerPoint presentation given in lecture prior to the lab, intended as the students' first introduction to fuel cells. Copies of any of these documents may be provided to interested parties upon request to the primary author (SC. York).

The largest potential problem associated with implementation of this laboratory is hydrogen generation and storage. The amounts of hydrogen used in the lab are very small, so reasonable caution eliminates serious safety concerns. However, generating and storing hydrogen always presents certain logistical and safety concerns. Generating hydrogen via solar-powered electrolysis is relatively slow and cannot be performed by the students in a 50-minute lab period due to time constraints.

To reduce lab start up time, we fill the lab hydrogen storage units prior to the students arriving in the lab. The electrolysers continue to run so that the hydrogen generation process is still readily visible. Students can mistakenly deplete their entire hydrogen supply very quickly and must then wait five to ten minutes while more hydrogen is generated. A larger hydrogen storage container has been designed and is currently being constructed. The larger storage capacity will allow a supply of hydrogen to be constantly available in the lab so that students may quickly refill their individual storage units when needed.

Equipment List

Item No.	Description	Source	Cost
1	dismantlable fuel cell	fuelcellstore.com	$132.50
2	Electrolyser	fuelcellstore.com	$339.00
3	solar module	fuelcellstore.com	$46.00
4	hydrogen storage cylinder	fuelcellstore.com	$89.00
5	75 watt lamp	Camera Corner	$120.00
6	Load measurement box	fuelcellstore.com	$98.00
7	low current motor	ABRA Electronics	$2.00
8	plastic tubing (25 ft.)	fuelcellstore.com	$5.00
9	cables (pair)	fuelcellstore.com	$6.95

Pre-lab Information on PEM Fuel Cells

Introduction:

Basic Characteristics

You have learned in lecture that PEM fuel cells are an important emerging technology involving multiple engineering disciplines. Performing this lab will help familiarize you with the basic characteristics and capabilities of fuel cells.

As with a battery or any other type of electrical power source, a fuel cell generates current in an electrical circuit. A given fuel cell will generate less current as resistance in the circuit increases. The inverse relationship between current and resistance is shown by Ohm's Law, which states:

$$V = I \cdot R$$

Where:

V = electrical potential (voltage) [V]
I = current [A]
R = resistance [Ω]

Ohm's law is only true for ideal systems in which no electrical energy is lost to heat dissipation. In an ideal system, the voltage measured in a fuel cell circuit would always equal the **cell potential**, which is the maximum voltage the fuel cell is capable of applying. In reality, the full cell potential is only achieved in an open circuit when there is no current and effectively infinite resistance. As resistance decreases and current increases, the fuel cell becomes less efficient and the measured voltage in the circuit is less than the cell potential.

The best way to represent the variation of a fuel cell's voltage at different levels of current output is to generate a **characteristic** curve. A fuel cell's characteristic curve is a plot of voltage vs. current output at varying levels of resistance. This curve is generated by applying different resistances to the fuel cell circuit and recording the current and voltage at each resistance. Corresponding values for voltage and current are then plotted. These values can also be used to generate a **power curve**, which is a plot of corresponding power vs. current values. Power is defined as:

$$P = V \cdot I$$

Where:

P = power [W]
V = voltage [V]
I = current [A]

Efficiency

A fuel cell's efficiency is calculated by two different methods. One of these methods is **Faraday efficiency**. Faraday efficiency is the ratio of the theoretical volume of hydrogen to the actual volume of hydrogen required for a certain current output and is expressed as:

$$\eta_{FARADAY} = \frac{V_{H_2\ theoretical}}{V_{H_2\ experimental}}$$

The theoretical volume of hydrogen is calculated from Faraday's 1st Law of Electrolysis, which states:

$$V_{H_2\ theoretical} = \frac{I\ t\ V_m}{z\ F}$$

Where:

V_{H_2} experimental = volume of hydrogen used [cm^3]
I = current generated by fuel cell [A]
V_m = molar volume of hydrogen = 24,000 [cm^3/mol]
z = number of electrons released by 1 molecule = 2 for hydrogen
t = time [s]
F = Faraday's constant = 96,484 [C/mol]

Faraday efficiency is a good way to compare fuel cells to each other, but not an accurate way to compare a fuel cell's efficiency to the efficiency of a different type power source. The best efficiency measurement for this application is **energy efficiency**. Energy efficiency is defined as the ratio of usable electric energy to the energy of the hydrogen that was consumed. Energy efficiency can be calculated by:

$$\eta_{ENERGY} = \frac{E_{ELECTRIC}}{E_{HYDROGEN}} = \frac{V_{cell}\ I\ t}{V_{H_2}\ H_l}$$

Where:

V_{cell} = measured fuel cell potential [V]
I = measured fuel cell current [A]
t = time [s]
V_{H_2} = volume of hydrogen used [cm^3]
H_l = heating value of hydrogen = 10.8 [J/cm^3]

References Cited

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[4] Ballard site. http://www.ballard.com/

[5] *Fuel Cells Explained*.

[6] *Heliocentric Product Manual*. Copyright Heliocentric 1999

[7] *Fuel Cell Experiments*. H-tec, Luebeck, Germany. www.h-tec.com

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