National Hydrogen and Fuel Cell Education Program Part II: Laboratory Practicum

Abstract

Hydrogen and fuel cell technologies (HFCT) hold the promise of cleaner transportation and reducing the US reliance on imported fuels. However, their introduction in technical curriculums nationwide is rather slow, while the demand for trained workforce for "research, development, and demonstration activities in government, industry, and academia" is growing. In 2008, the U.S. Department of Energy (DOE) made five awards to university programs seeking to develop and expand Hydrogen and Fuel Cells Education. The program is offered through California State University Los Angeles, Humboldt State University, Michigan Technological University, University of North Carolina Charlotte and University of North Dakota.

The participating universities are actively developing a variety of new curricula or modifications to existing majors. A detailed account of curricular activities is given by the authors in a sister publication[1]. Recognizing the inherent complexity of the topic and a multitude of new concepts, the HFCT programs are integrating laboratory practicum and projects supporting student learning.

Both equipment available on the market and custom-built laboratory units are discussed. Over the recent years, several manufacturers have come forward with HFCT equipment offerings. Equipment's performance, integration into courses and variety of adopted applications at several institutions are being presented in a single publication. In addition, descriptions of several custom experiments addressing specific needs in their respective programs are shared.

Introduction

In fall 2008, the U.S. Department of Energy (DOE) made five awards to university programs seeking to develop and expand Hydrogen and Fuel Cells Education[2]. The original solicitation sought to expand hydrogen and fuel cell technology awareness among the general public, decision makers and also develop professional educational programs. Five academic institutions throughout the country were selected to further expand the latter. The main objective of this section of the program was to train graduates who will "comprise the next generation workforce needed for research, development, and demonstration activities in government, industry, and academia[1]. The program is offered through awards to California State University Los Angeles, Humboldt State University, Michigan Technological University, University of North Carolina Charlotte and the University of North Dakota. Recognizing the inherent complexity of the topic and a multitude of new concepts, the HFCT programs are integrating laboratory practicum and projects supporting student learning.

This paper provides an overview of each participating institution laboratory practicum design and implementation after one and a half years of executing the program. While the funding was provided under the same DOE program, the paths, disciplines, courses, approaches of implementation, and choices were made independently. Therefore, a wide variety of ideas are presented. The authors share the accomplishments and challenges of integrating the experiments and projects into associated courses. Both equipment available on the market and custom-built laboratory units are included. Equipment performance, integration into courses and variety of adopted applications are discussed. In addition, descriptions of several custom experiments addressing specific needs in their respective programs are shared.

Commonly, publications dedicated to HFCT practicum are addressing experiments from home - built fuel cell/electrolyzer demonstrators[3, 4, 5, 6] to undergraduate research[7] or summer research projects for undergraduates[8]. In Shirkhanzadeh,[3] a thin-layer fuel cell is described that is particularly useful for teaching and classroom demonstrations combining both an electrolyzer and a fuel cell. Lin[4] and Fenton[5] in the Chemical Engineering Department at the University of Connecticut present a more comprehensive laboratory set up with a full set of experiments demonstrating the principles related to proton exchange membrane fuel cell. The fuel cell is set in a holistic environment that also includes solar panel, electrolyzer, and gas storage realizing great flexibility of topics supported. Ososanya[6] presents a 10V hydrogen fuel cell built by stacking 10 1volt single fuel cell as an experimental prototype fuel cell system designed for undergraduate studies. In Fletcher,[7] undergraduate engineering students participated in a long-term research which involved building a testing environment for a 1.2 kW fuel cell "to assess their performance, durability and reliability over a wide variety of operational and environmental conditions over a sixteen month period." The Student-Oriented Fuel Cell Project at Pittsburg State University[8] utilized the summer Research Experiences for Undergraduates (REU) program for "a "hands-on" education in the areas of design, development, formulation and fabrication of Molten Carbonate Fuel Cell electrolyte matrix support." All of these elements for introducing students to HFCT, in similar and different realizations, can also be found in this paper as well as comprehensive laboratory development undertaken by the individual programs.

With the focus of aiding the reader in setting up a more formal HFCT laboratory, a brief overview of the market based on the authors' experiences is shared. There are now many vendors that provide a variety of HFCT equipment from small experiments to larger units to fuel cells integrated with other alternative energy demonstrators. Identifying the best and most economical HFCT equipment can still be a challenge. Among the most notable companies that provide HFCT instructional laboratory equipment are Heliocentris, Horizon Fuel Cell Technologies (Horizon), US Didactic and Hampden Engineering Corporation. Many professional test equipment choices are also available. For example, UNCC selected a research grade fuel cell test stations from Scribner Associates.

Heliocentris is a German company with North American offices located in Canada. HFCT products are the main focus for the company. The company actively markets its products by demonstrating its equipment at fuel cell, energy related and engineering education conferences. Not surprisingly, various Heliocentris products dominate the independently made selections for the laboratories described later on in the paper.

Horizon operates from Singapore with production facilities in Shanghai. The product line is diverse from fuel cell racing cars to fully packaged fuel cell power plants in kW range. Horizon products are very convenient for small projects integration as shown in CSULA experiences. The company also provides custom built fuel cells as in CSULA unmanned aerial vehicle built in Dr. Chivey Wu's laboratory under separate funding.

US Didactic and Hampden on the other hand provide full spectrum of engineering laboratory equipment and fuel cell products are a few items on a long list. Their flagship units for fuel cell testing are *EHY1 Fuel Cell Trainer* and *Model H-FCTT-1 Fuel Cell Technology Trainer*, respectively. Both units are made from the components supplied by Heliocentris for its *The Instructor* training system. Thus, purchase of these units is justified if they are a part of a larger order from these vendors. US Didactic also offers a briefcase sized *AE 102 Hydrogen - Fuel Cell Trainer* for introductory activities.

The main intent of the paper is to aid other institutions in developing their strategies and approaches to introducing HFCT practicum presented in one publication. This is the very first effort of such kind in fuel cells. Those interested in obtaining materials are welcome to contact the authors. The associated HFCT curriculum development summary is reflected in a companion paper offered through the same forum[1].

California State University Los Angeles

HFCT practicum at CSULA has been developing in several pathways combining traditional laboratories, senior projects, graduate student research, and laboratory system integration. The main activities are in the Technology program offering Bachelor's in Industrial Technology with the emphasis in Power, Energy and Transportation (PET). Within the emphasis, the Fuel Cell Applications course is offered alongside such courses as Photovoltaic Systems and Electric, Hybrid and Alternatively Fueled Vehicles, and others. All of the courses are 50/50 lecture/lab format with six contact hours in a ten-week quarter. A concept of the "Zero Emissions Laboratory" was introduced to support fuel cell courses and to integrate fuel cell topics with other courses in the PET program, see Figure 1. The second course in HFCT that the laboratory will support is titled Fuel Cell Systems, which is a graduate course in mechanical engineering. When fully developed, the lab will introduce students to the concept of renewable hydrogen generation and utilization in fuel cell applications. The key features of the system are the solar installation, an electrolyzer, solid state hydrogen storage and a fuel cell application. The fuel cell, in turn, can power an electric motor testing on an electric motor dynamometer also available in the lab.

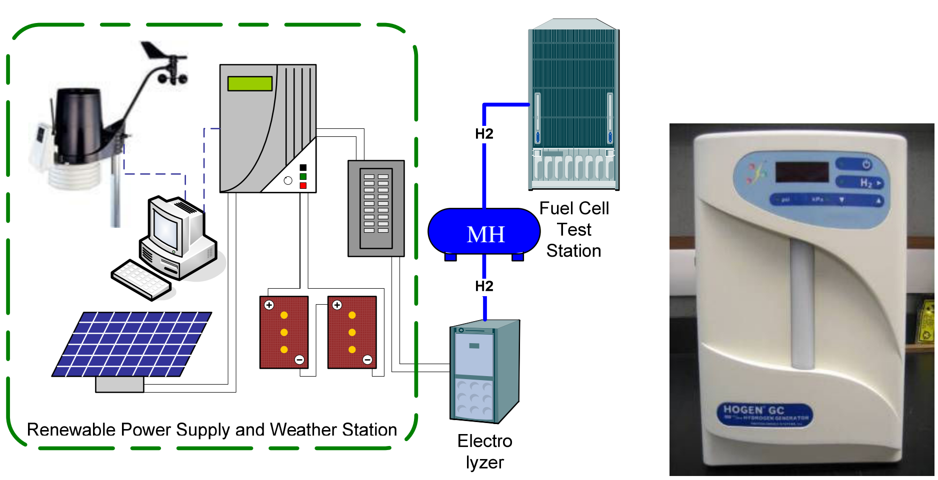

Figure 1. Graphical representation of the Zero Emissions Laboratory concept (left). HOGEN GC 600 Electrolyzer (right).

The solar installation is a work in progress. Under the grant, 2 kW of Solec panels were installed as the cost share on the grant. The panels were donated by Southern California Edison. That is in addition to previously installed 8 kW of Sharp panels. The balance of system is still being designed and most likely will integrate a multi-power-point-tracking 3-phase capable inverter.

The electrolyzer is the HOGEN GC 600 by Proton Energy Systems as seen in Figure 1. The produced hydrogen is to be stored in Ovonics metal hydride (MH) tanks. This hydrogen is used to power the Nexa Training System Complete by Heliocentris. It is noted that the metal hydride storage system is part of this package. The electrolyzer has not been integrated into the laboratory curriculum as it is still in the research phase for direct charging of the tanks.

The Nexa Training System Complete (NTSC), see Figure 2, is a state-of-the-art equipment by Heliocentris. It consists of a Nexa 1.2 kW Ballard fuel cell, on-board hydrogen storage, DC-AC converter, and variable load with data acquisition. German built, it is a high-quality product. The controls and data acquisition were intuitive and students were comfortable working with it. All system parameters are available from multiple information displays. The advantage of the NTSC is that it allows looking at the stack and system performance as opposed to a single cell and that it is a full application from storage to generation to load. It also provides a 120V outlet for external applications.

However, the NTSC does not come with any lab instructions. The graduate student working with the NTSC wrote a new set of basic operating procedures. In the first year, only an introductory lab was developed. It consisted of evaluating the fuel cell in three regimes: low, medium and full load. The changes in twenty some parameters were evaluated as well as energy flow was analyzed and compared with that displayed by the system as shown in Figure 2. The NTSC system will also be used for the graduate course and special projects.

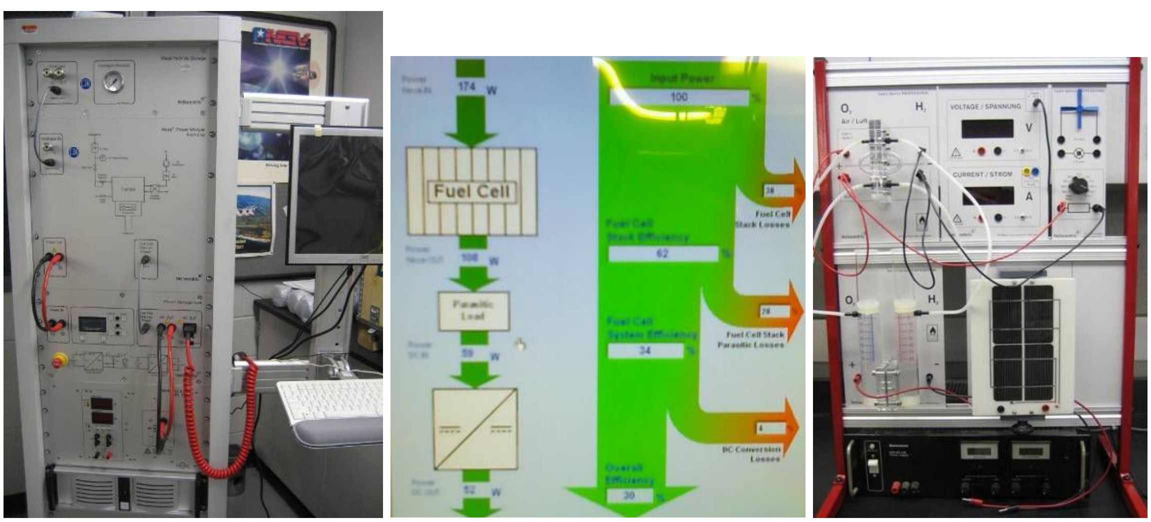

Figure 2. The Nexa Training System Complete (left). One of the NTCS data displays, system energy flow is shown (middle). Dr. Fuel Cell test stand (right).

Dr. FuelCell (DrFC), see Figure 2, unit is an affordable option for introducing various fuel cell and hydrogen generation concepts. The stand includes a dual fuel cell, electrolyzer, solar panel, ammeter, voltmeter, solar panel, motor and resistor loads. The unit comes with a set of lab manuals which address a variety of topics related to the modules on the stand. The manuals are bland, but will provide an initial guidance.

The unit is supposed to be powered by a light bulb through the solar panel. That option was ruled out as cumbersome and a DC power supply was used to generate hydrogen in the electrolyzer. The electrolyzer design is great and convenient. Its performance was the closest to the theory.

The fuel cells performed marginally with data somewhat inconsistent. One will have to be extremely careful to obtain quality data. The fuel cells would often flood and require regular blow through. The resistance load for obtaining the voltage-current curve on the fuel cell has ten settings, but only three-four could be used meaningfully toward the current-voltage curve.

The initial labs offered to students were enhanced versions of the labs provided in the manual. Based on this experience, which signaled the need, a graduate student was assigned to rewrite the manuals combining the labs, creating comprehensive set of instructions and sample calculations. The new lab manuals are related to lecture material and are designed with step-by-step procedures including detailed illustrations of DrFC modules, wiring diagrams and other items. Each lab has well-defined instructions in which students receive a brief description on the procedure and the expected fuel cell performance behavior. In two labs students obtain the electrolyzer and fuel cell's 1^{st} law efficiency, Faraday's efficiency, performance/power curves and other parameters.

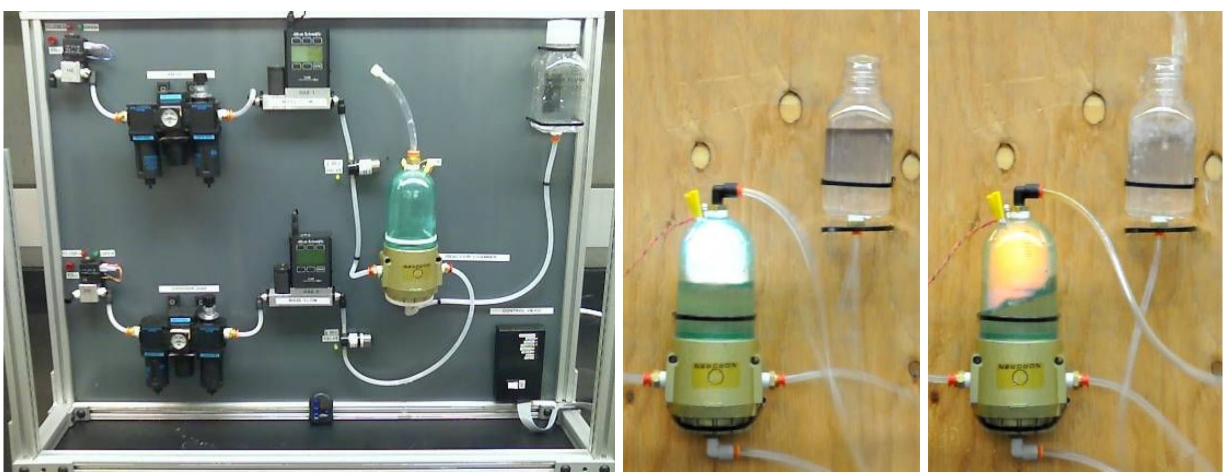

Figure 3. CSULA built Hydrogen Safety Experiment, safety shields removed (left). Gas explosions during prototype testing (middle and right).

Hydrogen Safety Experiment was a self-built experiment by a four-student senior design team, see Figure 3. It is built to demonstrate hydrogen/air/oxygen mixture explosive characteristics as it compares to other explosive gases available in the College of Engineering, Computer Science and Technology, such as methane, propane, and acetylene. The main goal is to demonstrate that other common gases are comparatively as dangerous as hydrogen but society accepts them.

The experiment is elegantly designed and is contemporary. For example, the February, 2009 issue of *Automotive Engineering International* presented an article[9] discussing a recent research into flammability properties of newer automotive refrigerants such as HFO-1234yf or R-744.

In the CSULA experiment, a water locked pressure vessel is filled with an explosive gas and air or oxygen and ignited. During the explosion, which could be spectacular, the pressure is relived through the water lock or pressure relief cap as it can be observed in Figure 3. Protective shields are installed in the frame when experiments are performed. All of the fill operations and the ignition are operated by a wireless remote. There will be no spark if the electrodes are touching the water.

Fuel Cell Test Stand. CSULA has obtained two research grade 25 cm^2 fuel cells. One is from Elctrochem and the other is from Fuel Cell Technologies. After initial failures in the membranes with which the cells were shipped, new membranes were installed and performance issues were resolved. An group of five students funded on a NSF REU (0552921) built a carbon-fiber test stand with temperature and flow controls as well as with an option of room temperature humidification of the air stream, as seen in Figure 4. The DC load unit is an affordable 300W TekPower 3711A. It is noted that 4 AWG wiring is recommended to avoid significant voltage losses in wiring to the load.

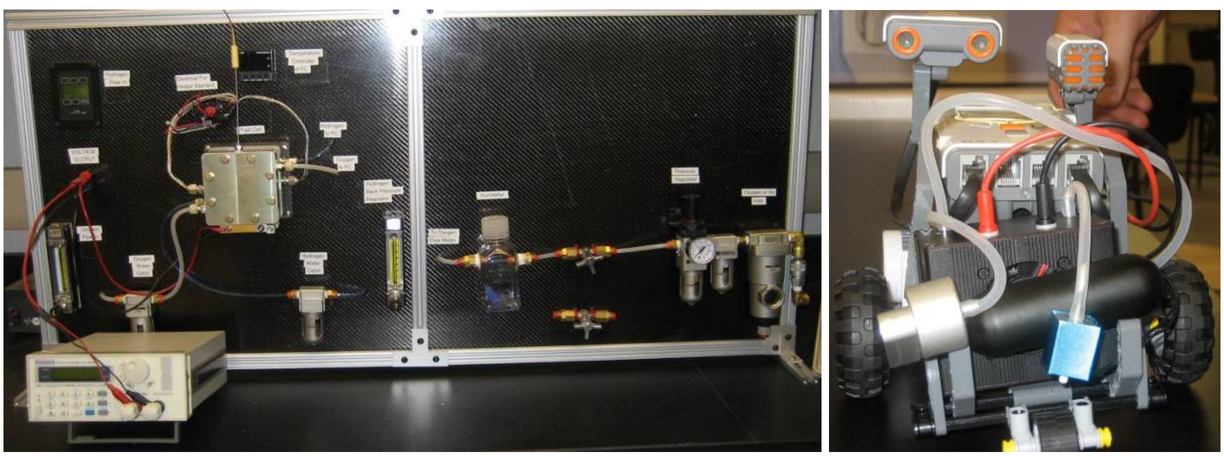

Figure 4. CSULA built fuel cell test stand with a 25 cm2 fuel cell (left). Lego MindStorm robot powered by a Horizon H-20 fuel cell (right)

Horizon Fuel Cells technologies is a Hong Kong based company producing a variety of portable educational and science oriented kits. CSULA has been working with a 20W H-20 fuel cell kit with an optionally purchased 20L solid state MH tank. The fuel cell has performed very well and is currently used to power a Lego MindStorm robot, as seen in Figure 4, which is believed to be the very first powering of Lego MindStorm using a fuel cell. A concern lies with the procedure necessary to activate the metal inside of the fuel tank, which must ship inactive. Pressure in excess of 30 bar is expected thus requiring a high-grade pressure regulator which is just as expensive as the fuel cell with the tank together. After the activation, the fill pressures are low.

Humboldt State University

The “Hydrogen Energy in Engineering Education” (H_2E^3) project is a three-year effort being led by the Schatz Energy Research Center (SERC), affiliated with Humboldt State University (HSU). One of the main objectives of the H_2E^3 project is to develop hydrogen teaching tools including a benchtop fuel cell/electrolyzer kit and a basic fuel cell test station suitable for use in university engineering laboratory classes. An additional project objective is to develop and deliver effective, hands-on hydrogen energy and fuel cell learning experiences for undergraduate engineering students.

The overarching purpose of the laboratory hardware and associated laboratory activities is to familiarize students with hydrogen and fuel cell technologies and prepare them for work in this field. Hands-on experiences with the fuel cell equipment are of real and immediate value, as the program also provides summer internships in coordination with the fuel cell industry.

Laboratory Hardware

The project focuses on two laboratory instruments for use in undergraduate engineering curriculum. Both instruments were designed and built by engineers at SERC.

A portable fuel cell test station for use in engineering laboratory courses. The educational fuel cell test station designed and built for this project synthesized design aspects of previous full-featured fuel cell test stations that SERC has designed, built, and installed for fuel cell research at three academic institutions (University of Michigan, Kettering University and Auburn University). A more basic version of the control and data acquisition capabilities of our full-scale test stations is combined with increased portability and schematic simplicity. Control and data acquisition software for operating the test station has been developed as well. The test station is compatible with a variety of single- and multi-cell PEM fuel cells up to 500 W output. Features include measurement and control of stack temperature, supply gas flow rates, and stack gas pressure. A programmable load allows operation at steady state, load cycling, or generation of polarization curves. The system is designed to connect via a USB port with a user-supplied laptop or desktop computer. Two complete test stations have been fabricated, one for use at HSU and other California State University (CSU) schools, and the other for use at the University of California, Berkeley (UCB) and other UC campuses, see Figure 5.One or more industry partners will provide fuel cell stacks for each of the test stations. We will work with our industry partners to develop the portable test station and associated software into a commercial product.

A set of 24 fuel cell and electrolyzer kits. Each of these kits includes a small alkaline electrolyzer, gas columns, a single-cell PEM fuel cell, electrical load, a DC power supply, connecting plumbing and wiring, current and voltage meters, and an instruction manual. The electrolyzer uses a 4.5 Molar (25 weight %) potassium hydroxide (KOH) electrolyte solution, which ensures high performance while minimizing safety hazard. Only the KOH solution and an AC electric outlet are required to operate the self-contained kits. The design for these kits was based on the kits SERC developed for high school fuel cell education with Lawrence Hall of Science as part of the DOE-funded Hydrogen Technology and Energy Curriculum (HyTEC) program[9,11]. The kits allow students to generate hydrogen and use the hydrogen to generate electricity with the fuel cell to operate electric loads, while measuring work performed and efficiency of each energy conversion. The new kits designed and built for this project are on a larger scale, more robust, and offer greater measurement precision and accuracy than the HyTEC models. Each individual kit can generate approximately 10 ml of hydrogen per minute and has a total storage capacity of 100 ml, see Figure 5.

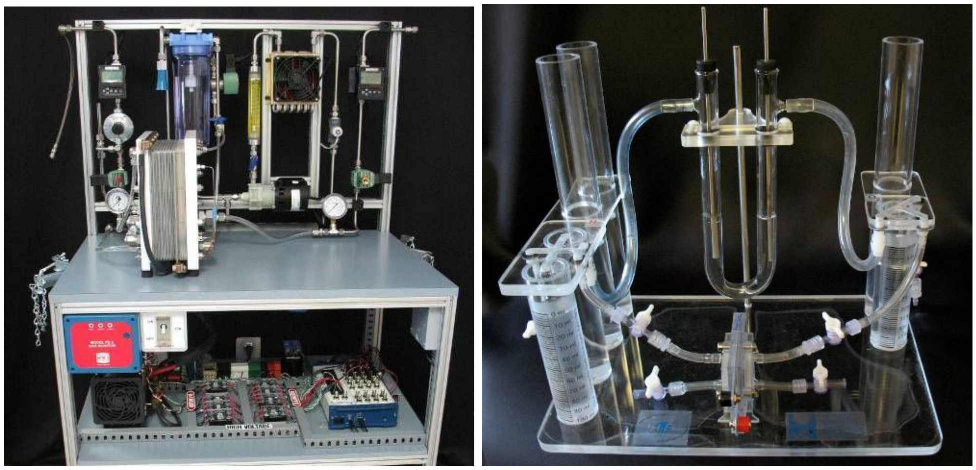

Figure 5. Hydrogen Fuel Cell Test Station (left). Hydrogen Fuel Cell Test Kit (right).

Curriculum

The H_2E^3 project curriculum modules are designed for use in existing engineering courses and will use hydrogen and fuel cell technologies to teach concepts and principles already integral to the curricula of courses. The goal is to allow teachers to replace existing lessons rather than to add lectures or activities to already tightly scheduled courses. Draft versions of curriculum modules will be designed for students in the following types of courses:

- introduction to engineering
- introductory thermodynamics
- advanced thermodynamics
- manufacturing engineering
- upper-division engineering laboratory
- energy and society

Curriculum components will consist of course-specific lesson plans, computer slide show presentations, recommended readings, laboratory activities (as appropriate), and problem sets with solutions. Depending on the course, topics may include: characteristics of hydrogen fuel; fuel cell electrochemistry and thermodynamics; fuel cell materials and manufacturing; fuel cell testing and evaluation practices; and the environmental, economic, and social aspects of a hydrogen energy economy.

Two courses, introduction to engineering and the first semester of thermodynamics at HSU, have implemented the benchtop kits in laboratory activities where students learn about the electricity-hydrogen-electricity cycle, in the process learning about the 2nd Law of thermodynamics and making electric power measurements, as in Figure 6. The fuel cell/electrolyzer kits allow students to generate hydrogen from water and grid or solar electricity, store the gas, and operate a fuel cell to power mechanical loads. Efficiency of every energy conversion step can be measured using provided instrumentation. In the thermodynamics course, the experiment was extended to measure the waste heat generated by the electrolyzer and discover how individual fuel cells are assembled in a stack to increase voltage and power production.

Figure 6. ENGR 115 Students at HSU using the H2E3 kits

Implementation of fuel cell/electrolyzer kits in Introductory Engineering course

Pilot testing of H_2E^3 curriculum and hardware began in the Fall 2009 semester, with the introduction of the materials in the ENGR 115 (Introduction to Environmental Resources Engineering) course at HSU. This class has 96 enrolled students and four separate lab sections taught by two instructors. The 115 curriculum was presented as a single three-hour lecture/lab activity in all four lab sections. The students were first given a brief presentation on electrolyzer and fuel cell electrochemistry, the ideal gas law, the use of Gibbs free energy, and calculation of electrical power using current and voltage data. The instructors explained how to use this information to calculate the efficiency of each energy conversion step in using electricity to generate hydrogen, then using the hydrogen in a fuel cell to operate an electric load. The instructors then gave a talk on safety, explaining the potential hazards associated with the fuel cell/electrolyzer kits and safe operating practices. The students completed wiring diagrams to show they understood how to operate the kits and measure current and voltage. Finally the students operated the electrolyzers and fuel cells, calculating efficiency for each step. A set of analysis questions prompted the students to consider the meaning of the lab activity and the underlying scientific concepts.

Students worked in groups of three to four using the electrolyzer fuel cell kits and the curriculum developed for the first lab activity. Researchers from the Schatz Energy Research Laboratory worked with HSU engineering faculty teaching the course and undergraduate lab teaching assistants to deliver and assess the fuel cell curriculum. The following assessment activities were implemented during this pilot activity:

- pre-assessment test completed by students
- post-assessment test completed by students
- focus group meeting with student teaching assistants
- group or individual meeting with HSU faculty

The feedback given by the students was overwhelmingly positive. Students really enjoyed being able to set-up their experiment and see how the fuel cell worked first hand. Many students commented that the lab was "fun", "awesome", and that they "liked", "enjoyed" or "loved" this lab. Of the 73 open-ended comments received, only four did not begin with a positive statement.

> "Using the multimeter within a system of circuits that I set up was my favorite part because I have always seen demonstrations like this but have never been allowed to actually do them myself".

> "This lab has piqued my interest in the hydrogen fuel cell technology. I have browsed the internet and now realize the wide variety of products being made that use this technology."

Students suggested three main areas for improvements. First they requested more time to complete the experiments and calculation. The first hour of the lab session was devoted to a lecture on how fuel cells work, how to set-up the wiring and complete required calculations. This suggestion can be accommodated by front-loading some of the introductory material in a lecture session.

The second suggestion related to confusion regarding the wiring. This is clearly an area that needs to be more carefully presented. In addition, instructors need to decide if understanding how to connect the wiring in the system is an important learning objective for the activity. If it is, more time may be required to adequately address that learning objective. If not, students could be instructed on the correct wiring setup, thus avoiding having to set aside significant lab time for the students to figure out this aspect of the activity themselves.

> "I was a bit thrown off by the whole wiring diagram. I do not know circuitry at all …, but it made me feel kind of bad to not know what was going on with all that wiring stuff. I really hope I am not supposed to know that, but just in case, I have been reading all about circuits online."

The last suggestion was in regards to the operation of the fuel cells themselves. It seemed several of the fuel cells became flooded during the experiment and did not run for the entire suggested three minutes of each run.

> "The fuel cell was losing voltage relatively quickly as the experiment was being run. I'm told that this was due to water build up in the fuel cell. Finding a way to keep this from happening would be good."

The most valuable lessons learned from the pre/post assessments include: 1) overall the students are improving both their comprehension of the learning objectives and their confidence about the subject matter; 2) parallel and series circuits remain confusing for the students; 3) there is also confusion about the system components and terminology, specifically the boundary between gas production (i.e. the electrolyzer) and gas storage, and 4) the introduction of material prior to the lab session will facilitate greater understanding of the exercise and allow for more time for the experiment and efficiency calculations.

We are currently in the process of further analyzing results to determine the specific actions with regards to: 1) hardware changes to fuel cell/electrolyzer kits, 2) editorial changes to the laboratory activity curriculum, and 3) editorial and implementation changes to Assessment Tools

Continued pilot testing of fuel cell/electrolyzer kits, laboratory activity curriculum and assessment tools is scheduled for the Spring 2010 semester in both Thermodynamics and Introduction to Environmental Engineering at HSU and UCB.

Future Development

We will continue to improve and develop curriculum for this project in particular for the use of the test stations in upper division engineering courses. Lab modules and assessment data will be posted to the project website (www.hydrogencurriculum.org).

Michigan Technological University

In this subsection we will describe the progress towards developing CM / ENT 3978: Hydrogen Measurements Laboratory at Michigan Technological University. Other aspects of the hydrogen curriculum at Michigan Technological University are described in a companion paper.

The course CM / ENT 3978 Hydrogen Measurements Laboratory is a one-credit elective laboratory taught within the Department of Chemical Engineering. It can be taken to fulfill requirements for an Interdisciplinary Minor in Hydrogen Technology or the Enterprise Minor. It is expected that the enrollment in this course will primarily consist of undergraduate students. Students completing the course should be able to:

- Measure characteristic curves for solar cells and fuel cells
- Use Faraday's law for electrolysis and fuel cell operation
- Exhibit mastery of basic fuel cell voltage, current, power, and hydrogen consumption calculations
- Be familiar with efficiency in energy systems

Within the laboratory, four separate experimental setups are available. These were purchased from Heliocentris and include a *Dr. Fuel Cell Professional* solar electrolyzer and fuel cell (1.7 W maximum power output), a 50 W *Instructor Basic Kit* fuel cell, a *1.2 kW Nexa Fuel Cell* with a *Variable Resistance Load*, and a *Dr. Fuel Cell Model Car*.

The eight laboratory experiments in the course (and the setup to be used) include:

- Solar Panel Characteristic Curve (Two-Cell Fuel Cell) – students will learn how changing the load (light source) affects the current and voltage through the solar cell. This cell will be used in follow-on experiments to produce hydrogen.
- Faraday's Law for Electrolysis (Two-Cell Fuel Cell) – students will verify Faraday's law for hydrogen production in the electrolysis unit and for hydrogen consumption in the fuel cell.

- Fuel Cell Characteristic Curve (Two-Cell Fuel Cell) – students will measure the current and voltage output of the fuel cell as a resistive load is varied for two single-cell fuel cells as well as for the two cells connected electrically in series and in parallel
- Current, Voltage, and Power in a Fuel Cell (50 W Fuel Cell) – Students will measure current and voltage output of a larger fuel cell, and scale up system to power a home.
- Faraday's Law for the Fuel Cell (50 W Fuel Cell) – students will measure the relationship between hydrogen flow rate and electrical current using Faraday's first law
- Efficiency of the Fuel Cell Stack (50 W Fuel Cell) – students will measure the current efficiency and voltage efficiency of the fuel cell stack and determine operating conditions to maximize efficiency
- Determine voltage, current, hydrogen consumption (1.2 kW Fuel Cell) Nexa – Students will power a 1.2 kW fuel cell using a variable load and determine the stack voltage and current as a function of the applied load. Students will perform basic fuel cell calculations including cell voltage, LHV efficiency, hydrogen consumption rate, and applied resistance.
- Hydrogen Fuel Economy (Fuel Cell Car) **–** Students will use a fuel cell powered car and measure the distance it travels with a certain amount of hydrogen and determine the "fuel economy" of this vehicle.

The course is to be taught for the first time in the Spring 2010 semester. There will be two sections of the lab (Tuesday and Thursday afternoon for two hours) with each section having a maximum enrollment of eight students, to be divided into teams of four. As of the writing of this paper, twelve students have signed up to take the course.

In the first week of the course, students will receive a laboratory tour and a lecture on hydrogen safety. The remainder of the course will be taught in cycles. Within each cycle are two experiments followed by a week to write up the laboratory reports. Thus, in one cycle the first team of students will perform experiment A in week one followed by experiment B in week two, and the other team of students will perform experiment B in week one followed by experiment A in week two.

The course grade is determined from performance on laboratory reports (80%) and performance on a midterm exam (20%). The course will be taught for the first time in the spring 2010 semester.

It is also noted that within this institution, students also can participate in the Alternative Fuels Group Enterprise and work on hands-on fuel cell and hydrogen technology projects. Aspects of the enterprise program are described in the companion paper.

University of North Carolina Charlotte

The HFCT program at the University of North Carolina Charlotte is designed to serve the needs of students intending to enhance their education from the Associate of Science or Associate of Arts level, of undergraduates entering UNCC directly and wishing to pursue a degree in HFCT, or of current professionals wishing to advance their technical skills to meet the needs of the future technology in HFCT. The program includes the development and delivery of undergraduate courses in the Engineering Technology Department within the Bachelor of Science in Engineering Technology program accredited by the Technology Accreditation Commission of the Accreditation Board for Engineering and Technology (ABET) (111 Market Place, Suite 1050, Baltimore, Maryland 21202 - Telephone 410/347-7700).

Two laboratory courses are planned as part of the HFCT program: the Fuel Cell lab and the Hydrogen lab. The Fuel Cell Lab is a one credit hour course that covers laboratory activities for fuel cell technologies. The fuel cell laboratory has research grade commercial fuel cell test stations from Scribner Associates, North Carolina, Model 850e+HT, see Figure 7. The test stations are designed to test Polymer Electrolyte Membrane (PEM) and Solid Oxide Fuel Cells (SOFC). The lab is also equipped with Fuel Cell Hardware, Conductivity Cells, Humidification System (with mass flow meter) and Comsol Multiphysics finite element modeling software. The lab experiments include lab safety, instrumentation, components and assembly, diagnostics and a student project. A 16 week schedule of the planned Fuel Cell Lab Course is shown in left two columns of Table 1. The objectives of the Fuel Cell Lab are to understand the usage of instrumentation to determine chemical and mechanical properties of fuel cell stacks, to assemble fuel cell components and operate fuel cell test and to conduct test and collect data on flow rates and efficiency.

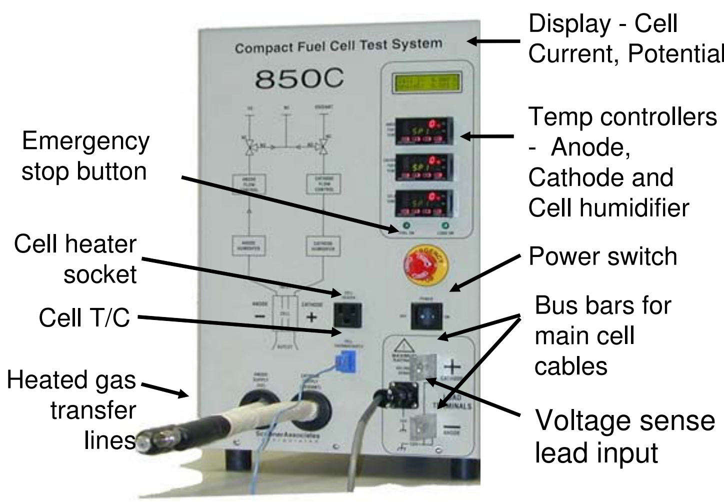

Figure 7. Front panel of the fuel cell test station used in UNCC fuel cell lab

Similar to the Fuel Cell Lab Course, the Hydrogen Lab is a one credit hour course that covers laboratory activities for hydrogen technologies including lab safety, instrumentation, storage experiments and a student project. A 16 week schedule of the planned Hydrogen Lab Course is shown in the right two columns of Table 1.

Both Fuel Cell and Hydrogen labs require the students to read the lab manual prior to each lab and submit a pre-experiment report as preparation for performing the scheduled experiment, conducting calculations, and discussing and interpreting results. Four types of written reports are required throughout the course: a pre-experiment report, a memo report, an informal report, and a formal report. Pre-labs are required for each experiment. After an experiment is conducted, either a memo report, informal report, or a formal report will be due. Below is a brief description of each report.

- *Pre-Lab Report (due at the beginning of each lab)* **P**
  The pre-lab is typically one page in length. It explains the hypothesis to be tested, describes the test set-up, and provides appropriate theory, governing equations, assumptions, and expected results.

- *Memo Report (due one week from the date the experiment was performed)* **M**
  This report builds on the pre-lab report and includes a brief discussion of what was or was not proven. It may include "distilled," tabulated data, sample calculation, discussion/conclusion and an appendix with raw data, diagrams and schematics.

- *Informal Report (due one week from the date the experiment was performed)* **I**
  This report contains a title page, summary, results section, and appendix.

- *Formal Report (due two weeks from the date the experiment was performed)* **F**
  This report is a comprehensive and detailed laboratory report following a specified outline. The appendix must include sample calculations but may also include raw data, diagrams and schematics.

Table 1: Fuel Cell and Hydrogen Labs Schedules

Subject	Report	Subject	Report
Introduction and Laboratory Safety		Introduction and Hydrogen Laboratory Safety	
Instrumentation	P	Gas Cylinder Safety & Handling	P, M
Fuel Cell Chemistry and Efficiency I	P,M	Instrumentation – Gas Chromatograph (GC), Thermo Gravimetic Analyses (TGA) and others I	P,I
Fuel Cell Chemistry and Efficiency II	P,M	Instrumentation – Gas Chromatograph (GC), Thermo Gravimetic Analyses (TGA) and others II	P,I
Electrochemistry I	P,I	Instrumentation – Gas Chromatograph (GC), Thermo Gravimetic Analyses (TGA) and others III	P,I
Electrochemistry II	P,I	Material Balance I (calibration of mass flow controller & humidifier)	P,M
Fuel Cell Components and Assembly I	P,M	Material Balance II	P,M
Fuel Cell Components and Assembly II	P,M	Characterization of Chemical Hydride Materials I	P,F
Break- No Classes- All Sections	NA	Break- No Classes- All Sections	NA
Operating Conditions I (pressure, temperature, humidity, flow rates)	P,F	Characterization of Chemical Hydride Materials II	P,F
Operating Conditions II (pressure, temperature, humidity, flow rates)	P,F	Hydrogen Liquefaction Experiments I	P,I
Fuel Cell Diagnostics I	P,I	Hydrogen Liquefaction Experiments II	P,I
Fuel Cell Diagnostics II	P,I	Student Project I	P,F
Student Project I	F	Student Project II	F
Student Project I	F	Student Project III	F

University of North Dakota

The University of North Dakota (UND) recognizes that fuel cells are being utilized in a wide variety of industry applications. Market trends demand a workforce educated in the operation and maintenance of fuel cells. To ensure that the next generation of engineers will be on the forefront of renewable energy technology, UND is incorporating fuel cell education into its engineering curriculum. Funds from the DOE award allowed UND to acquire several fuel cell systems, including a 50 W proton exchange membrane (PEM) fuel cell and a 600 W PEM fuel cell. This equipment is being used to facilitate teaching of basic fuel cell characteristics and operation.

Initial experiments are performed using a hydro-geniuses laboratory experimental setup. This equipment contains a solar cell, a single cell PEM electrolyzer, two single cell PEM fuel cells, and a small resistive load. Students generate I-V characteristic curves of the fuel cell and the electrolyzer and analyze system efficiencies. In this lab, the students are given a memo from their “boss” asking them to design a system to supply 100 kW of electricity. The students need to determine system efficiencies and power curves to propose a design. This experience exposes students to the basic elements of electrolysis and fuel cell operation.

Two new experimental setups were purchased from Heliocentris though the support of the DOE Hydrogen Education Program. The HP 600 includes a 600 watt water-cooled PEM fuel cell stack, a DC/DC and DC/AC converter, metal hydride storage kit, electric load, and an integrated control system. The off-grid instructor includes a 40 watt fuel cell with integrated microprocessor, electronic load, metal hydride storage, and the constructor kit. A Masters student has been developing a set of laboratories that will be implemented in to the undergraduate curriculum during the 2009-2010 academic year. Figure 8 provides photos of the equipment.

Figure 8. Heliocentris equipment used in UND laboratories. HP 600 (left) and the Instructor training systems.

An advanced fuel cell laboratory for junior- and senior- level, as well as graduate electrical and chemical engineering students has been developed using the 50W and 600W fuel cells. Operating under the assumption that the students have had exposure to fuel cell equipment through the previous lower level labs, this set of experiments works towards two objectives:

developing the voltage-current curve and measuring the effect of internal resistance. Emphasis is placed on these characteristics of the fuel cell stack as they are indicative of system performance. Through this process the students gain additional knowledge of basic PEM fuel cell operation and behavior.

In addition to performing the basic experiments to generate IV and power curves, an experiment was added to record individual cell responses to increases in load current. Ambient temperature (approximately 26 degrees Celsius versus stack temperature of approximately 40 degrees) impacts the performance of the outer cells, and therefore, the overall performance of the stack. However, it is assumed that the effect is minimal. Examining the performance of individual cells can help explain the overall behavior of the stack and is a good introduction for student investigation into the more complex reactions occurring in each cell, see Figure 9.

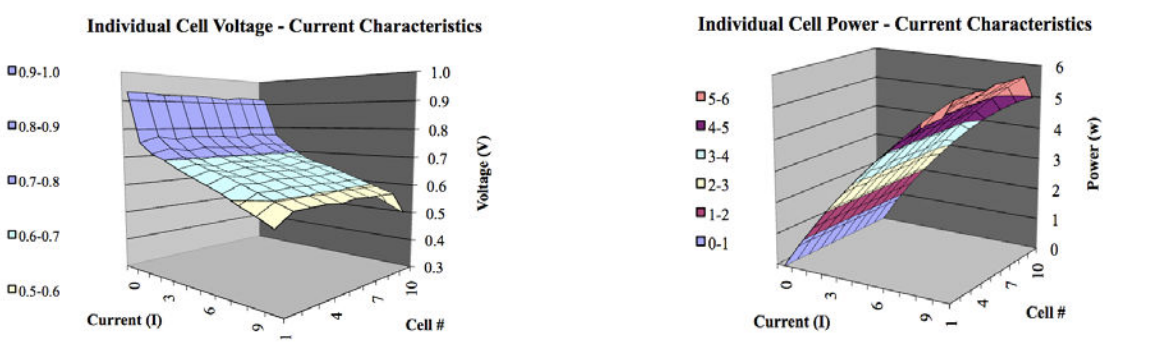

Figure 9. Characteristics IV and power curves developed during the lab

The consideration of voltage drop is also important when evaluating the performance of the fuel cell system. Comparison of the open circuit voltage potential of the stack and the system shows that there is resistance from the system components above and beyond resistance from the fuel cell stack itself. Examination of the trend of the voltage drop of the system versus the voltage drop of the fuel cell stack alone shows that there are other effects to take into account as the load increases. While this experiment does not examine these additional effects, it, again, serves as a good starting point for designing future investigations. Were this a comprehensive analysis of the fuel cell system, the broad end goal may be to determine whether it is a “good” or “bad” fuel cell stack. While different fuel cell applications have different specifications, the evaluation of system performance is generally a comparison of its ideal operation to its actual operation. Ideal operation is the most power produced for the fuel provided – or the greatest efficiency. This topic also begs further investigation and serves as a good exploratory discussion to incorporate into laboratory planning.

The obvious value for students of the experiments is that they will gain a better understanding of the way a fuel cell operates – specifically the relationship between voltage, current and power output. However, it is the manner in which the students gain this knowledge that should be the focus for educators. Students have the opportunity to perform the experiments described with minimal guidance. When problems arise, critical thinking is required to troubleshoot and find solutions. After the initial set of data is collected, following manufacturer load current increment recommendations, students propose additional experiments. This step requires imagination, and questions are posed and answered, such as what type of variations could be made on the original experiment in order to gather telling data.

ABET requires institutions of higher education to demonstrate that their students achieve a number of program outcomes. Several of these outcomes and objectives address the need for engineers who can apply knowledge from the classroom to real-world problems. The use of hands-on experiments designed to encourage student exploration is one of the ways UND prepares students to be successful engineers. Hands-on experiential learning allows students to supplement their classroom background with actual results and to improve critical thinking skills by developing and solving research problems of their own design. Details of these student laboratories are presented in a companion paper in this conference.

Conclusions

As a result of DOE funding, the HFCT education has made significant progress toward the goal of establishing effective programs and associated laboratory practicum and projects. The programs have demonstrated a variety of approaches taken to developing HFCT laboratory experiments.

The survey also finds that, despite many vendors that have recently come on the market of fuel cell educational equipment, Heliocentris equipment dominated as several independent PIs had selected products from predominantly one company. Another finding was that lower quality cells have tendency to flood resulting in inconsistent performance. Further development of products, such as those offered by HSU, can provide affordable alternatives and quality instructional materials.

Laboratory development is a long term investment for the participating institutions and future individual or collective updates are anticipated. Funding under the grant will continue for another year and a half. During that time the teams will make progress toward further growth of the individual programs and perhaps collaborate further as a result of this undertaking.

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