Extended Summer Research to Senior Design Project

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Introduction

There are many opportunities for undergraduate research to explore research experience and knowledge on Science, Technology, Engineering and Mathematics (STEM). The opportunities can come from senior design and/or summer internship. National Science Foundation Research Experiences for Undergraduates (REU) is one of the summer internship opportunities which has provided undergraduates with a substantial amount of research experience. A REU site reported that the REU undergraduate participants gained considerable hands-on experience, the ability to work with specialized equipment, and methods of engineering measurements as well as more experience about engineering research¹. At another REU site, it was asserted that benefits of the internship include offering graduate school research experience, improving students' academic performance and confidence, and having a lasting impact on their career paths². Hirsch et al. suggested that their REU program could provide preparing undergraduates to be more capable members of their profession³. Further, it was found that most participants in a summer research program in electrical engineering for minorities at Georgia Tech were either enrolled in graduate school or were planning to enroll within the next two years⁴.

Sores stated that Florida A&M University senior design projects used C-Stamp microcontrollers rather than topic-specific microcontroller for robot design. He also stated that C-Stamp microcontrollers are more student-friendly and allowed students to achieve successful outcomes⁵. Another senior project used individually coded RFID tags and motion sensors to monitor hospital staff as well as identify visitors⁶. Schowen reported that 75% of graduate students in chemistry programs at the University of Kansas, Texas A&M, and Kansas State indicated that their undergraduate research experience was a contributing factor in their decision to attend graduate school⁷. Also it was reported that undergraduate research participants were more likely to pursue graduate school^{8,9}. The literature reviewed indicated that both REU and the senior design projects were not extended to summer internship researches. It is assumed that the summer research and senior design may be hardly possible to continue after the projects are over because the projects are small and requires the same mentor and/or specific equipment.

This paper presents the results of a 15-month collaboration (two summers and one academic year) between the Engineering Department at Virginia State University (VSU) and the Hydrogen Energy Laboratory at Old Dominion University (ODU) on sustainable energy. The aim of the ODU REU Program is to motivate and encourage undergraduate students, especially those from underrepresented groups, to pursue advanced degrees and/or careers in science, technology, engineering, and mathematics (STEM). The ODU REU Program provided mentoring hands-on research experiences on sustainable energy, lab facilities, student offices and planned activities to

motivate and encourage undergraduate students, especially those from underrepresented groups, to pursue advanced degrees and/or careers in STEM¹⁰.

The teams of faculty and students from the VSU and ODU conducted research on fabrication of a light weight fuel cell stack with polymer bipolar plates and end plates based on the Horizon fuel cell stack. Two faculty members from ODU and one from VSU provided mentoring service to the participating student researchers in three phases. Phase I included REU internships at ODU for two VSU students and one student from University of Puerto Rico during summer of 2017. Phase II was a Senior Design Project that involved three students during 2017-2018 academic year at VSU, and phase III was finalizing the project by a VSU student during the summer of 2018 at ODU. The funding to support this REU internship came from a request for supplemental funds from the National Science Foundation (NSF) through the VSU grant. This project offered students with opportunities to explore electrochemical technologies for clean fuels production and applications to the participating students.

Research Background

Fuel cells are electrochemical devices for power generation, which can be used as sustainable energy systems for transportation, industrial applications, and back-up and off-grid power. Polymer Electrolyte Membrane Fuel Cell (PEMFC) is attractive because of its high efficiency, mild operating conditions, and carbon free emission. In PEMFCs, hydrogen gas is flowing through the anode side while oxygen flows through the cathode side as shown in Fig.1. The hydrogen molecules split into electrons and protons (positive hydrogen ions). The electrons flow through the external circuit, while the protons flow through the membrane to the cathode to react with oxygen ions and electrons, producing electricity and H_2O as a by-product.

Fig. 1. PEMFC Diagram.

When it comes to unmanned aerial vehicles (UAVs) as an industrial application, PEMFCs can support much longer flight endurance than internal combustion engine and battery do. In 2006,

it was reported that a 2.5 kg UAV powered by an 85 W average, Protonex Technology 110W peak PEM fuel cell flew for up to 3h 19min¹¹. Later, Lyon *et al.* demonstrated that their 16 kg payload UAV with 12 m wingspan successfully achieved 48 hours flight with the Protonex Technology Corporation 550-W PEM fuel cell in windy conditions and the fuel cell stack in the ~550-W system weighed about 0.5 kg¹². It was asserted that the fuel cell of the UAV showed five times more air endurance than lithium-ion batteries and the lightweight fuel cell system can offer a long flight endurance for UAV¹³. The bipolar plate and end plate are usually the heaviest parts of PEMFCs. A bipolar plate provides a pathway for fuel, air, and water, separates the unit cells in the stack, carries current away from the cell, and supports the membrane electrode. This fact implies that it is possible to make lightweight PEMFCs if bipolar plate and end plate can be fabricated with light material such as polymer.

People have employed compression molding^{14,15,16} and injection molding to make fuel cell components using polymer and/or other material¹⁶. Suherman *et al.* employed a hot-pressing technique to make epoxy/carbon black/graphite composite for bipolar plates in PEMFC to investigate electrical conductivity of the composite¹⁷. Additive manufacturing (3D-printing) was implemented to make titanium-alloy bipolar plates with embedded flow channels using direct metal laser sintering¹⁸. These approaches allude that polymer 3D-printing and electroplating have not been applied to fabricate polymer bipolar plates for PEMFCs. Therefore, this research focused on fabricating a light weight fuel cell stack with polymer bipolar plates and end plates based on the Horizon fuel cell stack. The stack components, including end plates, bipolar plates, and interconnects were redesigned and fabricated to replace corresponding heavy components. Additive manufacturing (3D printing) and electroplating were used to fabricate bipolar plates and interconnects. The fabricated lightweight PEMFC stack was evaluated and compared with the standard performance. The next section describes the first phase of the research, 2017 REU Summer Research.

2017 REU Summer Internship

For the 2017 REU Summer Internship, three students were involved with a lightweight PEM fuel cell stack research project at the Hydrogen Energy Laboratory, Old Dominion University (ODU), Norfolk, Virginia from May 29 to August 3, 2017. To overcome the excessive weight, the graphite bipolar plates, collectors and aluminum end plates of the fuel cell were redesigned using lightweight materials because they were the heaviest. First, the bipolar plates, collector plates and end plates were designed using CAD based on Horizon 100W fuel cell parts for ground applications (see Fig. 2). The dimensions closely followed that of Horizon's bipolar plate. Thirty-three straight channels for the air flow were made for air flow as shown in Fig. 3. The collector plates were identical to the bipolar plates except the electrodes which collect electrons. Then, the CAD files of bipolar and collector plates was uploaded to the Monoprice 3D printer to fabricate with PETG (Polyethylene terephthalate glycol-modified).

The end plates designed using CAD are shown in Fig. 4. The size of the end plates closely followed the Horizon fuel cell. One end plate was used for hydrogen intake and exhaust (Fig. 4a) and the other one is its counter side (Fig. 4b). The end plates were machined from Garolite XX plates using the dimensions specified in the design. Having replaced the metal materials and graphite bipolar plates of the Horizon 100W fuel cell with similar plastic counterparts, each

component's weight was measured to obtain the exact weight reduction of the fuel cell stack. The total weight of Horizon fuel cell stack was 384 grams whereas that of the fuel cell stack made in this research 170 grams. This means 56% weight reduction was achieved.

Fig. 2. Horizon 100W fuel cell stack for ground applications.

Fig. 3. Bipolar plate (Horizon design with 33 straight flow channels).

Fig. 4. (a) End plate for Hydrogen Intake and Exhaust and (b) End plate for counter side.

Figure 5(a) shows the image of 3D-printed collector plates. Since the Polyethylene Terephthalate Glycol (PETG) filament is an electrically insulating material, copper-painting and electroplating were used to make the 3D-printed PETG bipolar plates conductive. The electroplating was selected because it provides a more even electroplating of the fuel cell components than the typical painting method would alone. Two collector plates were copper-painted with Caswell copper solution first and then gold-electroplated with Caswell gold electrolyte. The fuel cell with the electroplated plates was tested at the same day when the gold-electroplating was completed. Fig. 5(b) and (c) show the image of copper-painted and gold-electroplated collector plate, respectively.

Figure 5. 3D-printing, copper-painting, and electroplating of collector plates.

Lightweight fuel cell stack assemblies and testing

Before testing the lightweight fuel cell, a 100 W Horizon fuel cell stack with two membrane electrode assemblies (MEA) and two graphite bipolar plates were tested for a blank test to collect voltages versus current density data (see Fig. 6). This blank test was used to examine the reliability of the instrument. The testing procedure followed is described in reference 19. Fig. 7 shows voltage versus current density obtained from this test. The characteristics of the measurements was similar to the manual of the Horizon H-100 fuel cell stack²⁰.

Fig. 6. Horizon 100W fuel cell stack with two bipolar plates and MEAs.

Fig. 7. The polarization curve obtained from the Horizon H-100 Fuel Cell Stack with two graphite bipolar plates at 100 ml/min flow of H₂.

After the blank test, two collector plates of the same Horizon fuel cell were replaced with PETG plates which were gold-electroplated. The assembled fuel cell stack was tested with the same previous conditions. An open circuit voltage was detected around 0.75V, but the load current was not detected by the tester (see Fig 8). This means the potential was built up due to charge accumulation, but charge was not flowing through the load circuit. It was speculated that this was caused by an uneven surface of gold-plated areas, misalignment of bipolar plates and membranes, and/or unknown factors. Because of the limited time for the summer internship, this task was transferred to a senior design project.

Figure 8. The polarization curve obtained at 100 ml/min flow of H₂ from the fuel cell with two gold-electroplated collector plates.

ODU REU Site Project Evaluation was used to assess student participation in summer internship on three assessment tools: evaluation of scientific research papers, observation evaluation in the lab, and evaluation of presentations¹⁰. Evaluation of scientific research papers was made in terms of scientific knowledge, problem solving skills, and ability to communicate findings. The ODU mentor selected the project before the students arrived at ODU. The mentors and students held meetings almost daily to give advice as well as observe student performance. In the meetings, the mentors suggested that the students look at relevant publications; e.g., find lightweight materials such as Garolite XX. In the later stages of the literature survey evaluation, students found solutions from literature without mentor's assistance. This evaluation was very critical at the beginning of the research because the research plan was based on the scientific knowledge and problem-solving skills. Also, the performance of students was assessed during the weekly meeting. The students reported the previous week progress and mentors assessed the progress and provided suggestions for future tasks.

Observation evaluation in the research lab was conducted in terms of the change in students' level of interest, hands-on laboratory skills in designing and building alternative energy products, use of tools, and use of appropriate methodology for data generation. This evaluation was conducted almost daily because laboratory activities included experimental setup, testing, data analysis and safety. Problem solving and communication skills were also evaluated in the laboratory. Finally, the evaluation of presentations was conducted in terms of academic content,

quality of visual materials, and quality of communication. The students conducted mid-internship presentations and poster presentations as well as submitted a final report for the project assessment. All the activities including the problem-solving process and recommendations were well-documented in the final report. All of the students who participated acquired an intensive and publishable research experience. It is believed the report will surely help future REU research teams achieve their project objectives in a more efficient manner.

Three students demonstrated above-average of the ODU REU Site Project Evaluation which met the assessment target. The students professed this REU project significantly improved their confidence in proposing ideas, designing, problem-solving, experiments and data analysis. They were very satisfied with opportunity to participate in clean fuel production and applications as well as communicating with scientists and students at ODU. Their excellent work was rewarded through an undergraduate conference, in which they won Best Oral Presentation in Engineering from 2017 WBHR-LSAMP Annual Summer Research Symposium held at Morgan State University, in Baltimore, Maryland on July 27, 2017.

2017-2018 Senior Design

After the summer, three new VSU students took over the fuel cell project from the REU Internship group. This included the problem in which no current was detected. A uPrint SE 3D printer was used to make two collector plates because this printer produces the parts more accurately and faster than the Monoprice 3D printer. With the assumption that this problem was caused by uneven electroplating during the electroplating process and/or lack of the time allotted for nitrogen cycling, this time, the electroplating was allowed enough time to dry before a second coat was applied as well as longer nitrogen cycling. Also, it was ensured that all targeted areas were painted, and electroplating was applied evenly. After two collectors, two graphite bipolar plates, and two MEAs (membrane electrode assembly) were assembled with other parts, the fuel cell stack was tested. This newly assembled fuel cell stack was able to produce a measurable voltage and current density as shown in Fig. 9. In figure 9, the dotted line and triangles represent voltage versus current density whereas the dotted-dashed curve and circles represent power density versus current density. The triangles and circles are raw data. The line and curve were obtained from best fitting. The maximum power density estimated is 60 mW/cm² with 0.5 V and 150 mA/cm². The statistics estimated gives $P = -2.6584I^2 + 0.8433I - 0.0064$; $R^2 = 0.8489$ in which P is power density and I is current density. There was a deviation noticed in Fig. 9. $R^2 = 0.8489$ supports this deviation. It was verified that the deviation came from the small number of electroplated plates. The next experiment proved that the eight electroplated plates that were used showed significantly less deviation. Because of limited time for Senior Design, this task was transferred to another summer REU Internship project.

Fig. 9. Voltage and power density versus current density.

The Senior Design project followed seven ABET Student Outcomes which were used for the VSU Computer Engineering and Manufacturing Engineering Senior Design Course. The Student Outcomes assessed were: ability to design and conduct experiments, analyze and interpret data; design a system, component, or process to meet desired needs within realistic constraints; identify, formulate, and solve engineering problems; an understanding of professional and ethical responsibility; and communicate effectively. The project advisor and senior design course advisor shared the responsibilities to advise students and evaluate their performance. The project advisor advised them to design a fuel cell stack system that would meet desired power output, conduct experiments, analyze and interpret data, and solve engineering problems. Before the students started the course, the project advisor selected the project topic which was the continuation of the 2017 REU summer internship project.

The course advisor instructed students once a week on topics including: how to write a project proposal, share responsibilities, design realistic constraints and marketing requirement, map timeline, identify professional and ethical responsibilities, present collected data, and communicate effectively. Once a week, the course advisor assessed students' performance on course assignments and the project advisor evaluated students' project performance. Three students demonstrated above-average of the project evaluation which met the assessment target. The STEM abilities that students acquired from the senior design include (1) analyzing relevant research papers and applying their contents to the research, (2) circuit design of the fuel cell stack, (3) design and fabricating of fuel cell stack components, (4) testing the fuel cell stack (5) analyzing the experimental data, and (6) presentations of the research results at undergraduate conferences. The students stated that this senior design project significantly improved their confidence in problem-solving and experiments. They were pleased with an opportunity to conduct the fuel cell stack testing at ODU and communicate with scientists and students at ODU.

Another student took over the fuel cell project from the Senior Design team with the minor problem in which the fluctuation of voltage and current data was observed ($R^2 = 0.8489$). In order to reduce the fluctuation, the eight electroplated plates were used and tested with the experimental setup shown in Fig. 10. Both electroplating and testing were conducted together on the same day to minimize the oxidation of copper. After verifying the electroplating performance, the final fuel cell stack was assembled with six electroplated bipolar plates, six MEAs, two electroplated collectors and other parts. The assembled fuel cell stack was tested at 100 ml/min, 200 ml/min, and 300 ml/min of H_2 . Figure 11 shows voltage and power density versus current density obtained at 100 ml/min flow of H_2 . The maximum power density which was estimated from the curve-fitting equation is 3.514 W/cm^2 with 4.5 V and 1.6 A/cm^2 conditions. This figure shows less scattering compared with two electroplated plates. The scattering statistics estimated gives $P = -0.215I^2 + 0.688I + 0.0353$; $R^2 = 0.9492$ in which P is power density and I is current density. The R-square value confirms that the deviation previously noticed came from a small number of electroplated plates.

Fig. 10. Experiment setup for the lightweight fuel cell stack.

Fig. 11. Voltage and power density versus current density obtained at 100 ml/min flow of H_2 from the fuel cell stack with six bipolar plates and two electroplated bipolar plates

ODU REU Site Project Evaluation was implemented in a similar manner to 2017 REU Summer Internship. One student conducted this project at ODU. The student demonstrated above-average of the ODU REU Site Project Evaluation which met the assessment target. He was very gratified with the opportunity to participate in clean fuel production and applications as well as communicating with scientists and graduate students at ODU. The student won a travel award from Emerging Researchers National (ERN) Conference in STEM in Washington, D.C., February 21- 23, 2019. It is hoped that the REU and senior design participants will pursue advanced study on sustainable energy such as fuel cell in their future professional and/or academic career.

Conclusions

Two 10-week summer REU internship teams and a 1-year senior design group carried out a 15-month research journey to create a lightweight PEM fuel cell for unmanned aerial vehicle. The REU research was conducted at the ODU REU Site whereas the senior design was performed at VSU and its testing was also done at ODU. The bipolar plates, collector plates, and end plates of a lightweight fuel cell stack were designed and fabricated using polymer. Additive manufacturing (3D printers) and electroplating were implemented to make these components. The fuel cell stack was tested with a Scribner fuel cell test station. The maximum power density of the fuel cell stack observed was 3.514 W/cm^2 at 100 ml/min flow of H_2 . The internship research was assessed with three REU Site Project Evaluation tools. The senior design project was assessed with seven ABET Student Outcome evaluations. All the research activities including problem-solving process and recommendations were well-documented in the final reports. It is believed the report will assist future REU research and senior design teams to achieve their project objectives in a more efficient manner. REU internship and senior design students demonstrated above average of ODU REU Site Project Evaluation and Students Outcome evaluations, respectively. The students who participated acquired an intensive and publishable research experience. The research results were presented at engineering undergraduate conferences. It is hoped that the participants will pursue advanced study on sustainable energy such as fuel cell in their future professional and/or academic career.

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