SAC Undergraduate Research Program

HYDROGEN FUEL CELL VEHICLE - ELECTRICAL SYSTEM PERFORMANCE

Final Report

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EXITOS
Camino hacia el Exito

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Abstract

Engineering students from San Antonio College (SAC), with assistance from SAC faculty, industry contacts, and the Texas State University ReEnergize Program, are working to develop a prototype hydrogen fuel cell vehicle (HFCV) to compete in the prestigious Shell Eco-Marathon Americas event in Detroit in April, 2017. Shell Eco-Marathon challenges student teams to design, build, test and drive ultra-energy-efficient vehicles. To prepare for the competition, 20 engineering students formed the SAC Motorsport Team and, since September, 2015 have worked hundreds of hours researching, designing, and selecting equipment/materials for the HFCV.

In order to compete effectively in Shell Eco Marathon there was a need to better understand how the H-1000XP Hydrogen Fuel Cell Stack (HFCS) performs under different circumstances to find its most efficient operational configuration. This research project was set up to address this need. HFCS performance was tested with two different variables being controlled; i.e., the hydrogen gas supply pressure and HFCS output load. During testing the supply pressure varied from 7.25 psi to 9.25 psi and output loads varied from 87 Watts to 867 Watts. At the same time fuel (hydrogen) consumption in liters/min was measured. With this data charts were produced showing the fuel efficiency in Watts/liter/min for different input gas pressures and output power levels.

Test results showed that HFCS fuel efficiency at output power loads of 87, 125, and 164 watts was highest at lower input gas pressures (7.25 to 8.5 psi), and dropped substantially at higher gas pressures. At the four highest output loads (214, 401, 553, and 867 watts), the fuel efficiency was fairly constant at input gas pressures of 7.75 psi and above. The objectives of this research project were met; i.e., a better understanding of HFCS operation and determining its most efficient operational configuration. Future testing will determine if the results obtained with resistive loads will be similar to those obtained when the HFCV motor is connected as the output load.

Participants and Acknowledgements

Participants

Klaus B. Bartels - Faculty Adviser

Julio Banda - Team Leader

Amisadai Trinidad - Team Member

Irene Salazar - Team Member

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Susan Paddock -Professor and LSAMP-CIMA Co-PI

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Introduction

According to the *Alternative Energy: Alternative Energy Solutions for the 21st Century*, in 1802, a British chemist named Humphry Davy, studied the separation of hydrogen and oxygen molecules in water using electricity. This process became known as electrolysis, in which the idea of fuel cell technology began. While working with this concept, Sir William R. Grove, continued Mr. Davy's research and found that it was possible to reverse electrolysis, which is the combining of hydrogen and oxygen atoms together to create an electrical current. With this discovery, it led Mr. Grove to invent the first hydrogen fuel cell in 1839.

Alternative energy sources, such as a hydrogen fuel cell stack, is not only a replacement for fossil fuels, but an environmentally friendly option as well. Hydrogen fuel cell vehicles are more effective in helping our environment by only producing distilled water as "exhaust." This is unlike manufactured vehicles that are made to run on gasoline and emit harmful pollutants and greenhouse gases that negatively affect our nature and atmosphere. As we progress more with technology every day, we are finding out that hydrogen powered vehicles could be the alternative energy source to power the vehicles of tomorrow.

Following Humphry Davy and William R. Grove, we are expanding our knowledge in hydrogen fuel cell research to learn more about how to use this eco-friendly technology. Engineering students from San Antonio College (SAC), with assistance from SAC faculty, industry contacts, and the Texas State University ReEnergize Program, are working to develop a prototype hydrogen fuel cell vehicle (HFCV) to compete in the prestigious Shell Eco-Marathon Americas event in Detroit in April, 2017. Shell Eco-Marathon challenges student teams to design, build, test and drive ultra-energy-efficient vehicles. To prepare for the competition, 20 engineering students formed the SAC Motorsport Team and, since September, 2015 have worked hundreds of hours researching, designing, and selecting equipment/materials for the HFCV; i.e., wheels/tires, steering/suspension, frame/body, motor/motor controller, and the hydrogen fuel cell stack (HFCS).

In order to compete effectively in Shell Eco Marathon there was a need to better understand how the H-1000XP Hydrogen Fuel Cell Stack (HFCS) performs under different circumstances to find its most efficient operational configuration. This research project was set up to address this need.

With that in mind, the objective of our research project is to test a hydrogen fuel cell system, called a hydrogen fuel cell stack (HFCS), to determine its most optimum operational configuration from a fuel efficiency standpoint. With this knowledge, we will contribute significantly to the end goal; i.e., to produce a prototype hydrogen fuel cell vehicle that uses the least amount of hydrogen gas during the Shell Eco-Marathon competition, thus winning the competition.

Materials and Methods

Materials

A wide range of materials and equipment was used to perform the testing and ensure results were accurate and completed with safety in mind. The vendor, cost, and specifications of the materials/equipment used is seen in Table 1 below.

Equipment/Part Name	Source	Cost	Specifications or Description
H-1000XP (Hydrogen Fuel Cell Stack)	Hydrogen Fuel Cell Store	$8,999	- 0-48V - 0-33A
Hydrogen Fuel Cell Controller	Hydrogen Fuel Cell Store	$0*	- Output 12V - Output 48V
Load Resistors	MESA Center Workshop	$0	- 200 Watt - 8 ohms (each)
LCD Screen	Hydrogen Fuel Cell Store	$0*	- Displays current, voltage, and other specifications of fuel cell
Hydrogen Leak Sensor	Hydrogen Fuel Cell Store	$0**	- Alarm triggers at 1% H_2 concentration in the air - Triggers at 25% of the Lower Flammability Limit
Pressure Regulator	Zoro	$262.18	- H_2 Purpose - Delivery 0 psi -50 psi
Flow Meter	Vogtlin Instruments	$1027.86	- 2.9 psi to 159 psi - L/min displayed
Pressure Gauge	Amazon/Winters	$12	- 0-15 pounds per square inch reading range
Hydrogen Gas Tank	San Antonio College Chemistry Department	$0	- Pure H_2 gas - Gas pressure > 2,000 psi
Ventilation Hood	San Antonio College Chemistry Department	$0	- Removes leaked gases from the air by constantly replacing air in the ventilation hood

Multimeter/ Thermometer	Engr/Physics Supply	$0***	- Used to measure the resistance and temperature of the load resistors

* Indicates the component/part was purchased with the H-1000 XP
** Indicates the component/part was purchased with the DC/DC Converter
***Indicates the component/part was borrowed
**** Indicates the component/part was donated

Table 1 - Components and Parts List

Hydrogen Gas Tank

While the hydrogen tank was not moved nor touched, aside from opening and closing the valve located on top of it, it should be noted that testing would not have been possible without it. The tank was located next to the ventilation hood used for testing, stood more than four feet in height, and its contents were stored by a pressure greater than 2,000 pounds per square inch (psi). Due to the tank size it was not possible to be placed in the ventilation hood, but soap and water was used to find any potential leaks, none were found. The San Antonio College Chemistry Department allowed us the use of the hydrogen gas tank and made the testing possible in a chemistry lab as well.

Pressure Regulator

The regulator was used to reduce the previously mentioned pressure of the hydrogen tank to a safer and more suitable level for testing. On the regulator were two pressure gauges and a knob. These were used to measure the gas pressure inside of the hydrogen tank, measure the output gas pressure produced by the regulator, and to increase or decrease the output pressure supplied to the HFCS.

Pressure Gauge

Despite the pressure regulator gauge being able to read the output pressure, another gauge was needed to perform the same task. The gauge on the regulator was not able to display the specific pressure ranges (see *Table 1*) that were vital for testing process, therefore, another pressure gauge was used for a more precise reading.

Flow Meter

This was used to measure the rate at which gas was being supplied to the HFCS. Furthermore, the HFCS had a limit as to how high the flow rate can be before potentially damaging it. With the flow meter we were able to know if the limit was near or at the already set limit.

Hydrogen Fuel Cell Stack (HFCS)

Electricity generated by the HFCS was dissipated by the various load resistor configurations and also powered peripheral components (i.e., hydrogen fuel cell controller, HFCS cooling fans, LCD screen).

Hydrogen Fuel Cell Controller (HFCC)

Similar to the hydrogen gas tank, the HFCC was not moved nor touched, but did play an important role for testing. In order for the system (i.e., HFCS, hydrogen leak sensor, LCD screen) to work properly the HFCC controller was needed so all components worked as intended and with each other. The HFCC can be thought of as the brain of the system due it being the source of communication between the components.

Hydrogen Leak Sensor

The sensor was used as a safety component during testing. Had the sensor detected above normal amounts of hydrogen in the air, it would have turned the HFCS off, closed a valve that supplied the HFCS with hydrogen, and begin to make beeping noise.

LCD Screen

The LCD screen was used to know the HFCS performance status (e.g., stack voltage, stack current, ambient temperature). This was important part for testing as it gave the current and voltage rating of the HFCS.

Load Resistors

The resistors were used as load for the HFCS to help find how different size loads affected the performance of the HFCS. Furthermore, the power output of the HFCS was dependent on the resistive load connected to the HFCS electrical output. In addition, a voltmeter with a thermometer capability was used to make sure the load resistors did not overheat while going through different power levels.

Ventilation Hood

For safety purposes testing was conducted with the use of a ventilation hood, had any hydrogen gas leaked from the system, it would have been disposed of properly and away from anyone.

Digital Multimeter/Thermometer

Before testing the different load resistor configurations, it was taken into account that the resistors would generate heat due to the power output from the HFCS. To make sure they didn’t reach temperatures that would damage the resistors or cause harm to the team members a thermometer probe attached to the digital multimeter was used. The multimeter also had a resistance reading capability that was used to measure the individual resistors and their total resistance when connected in different configurations.

Test Setup

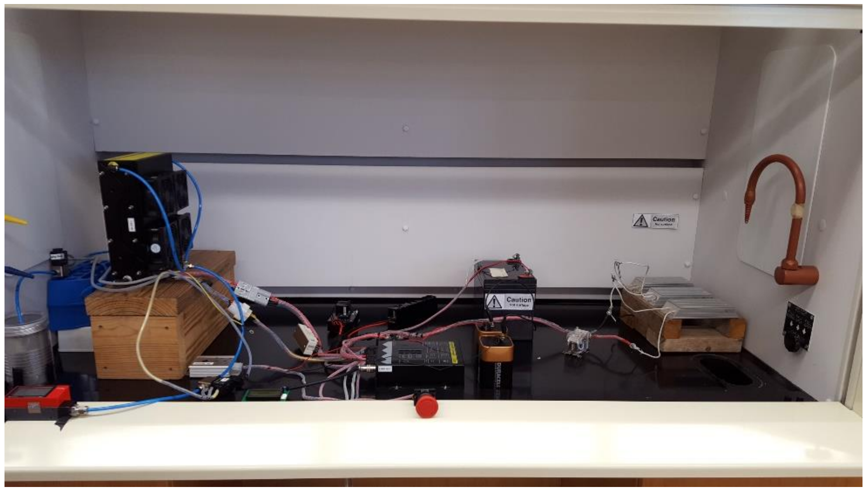
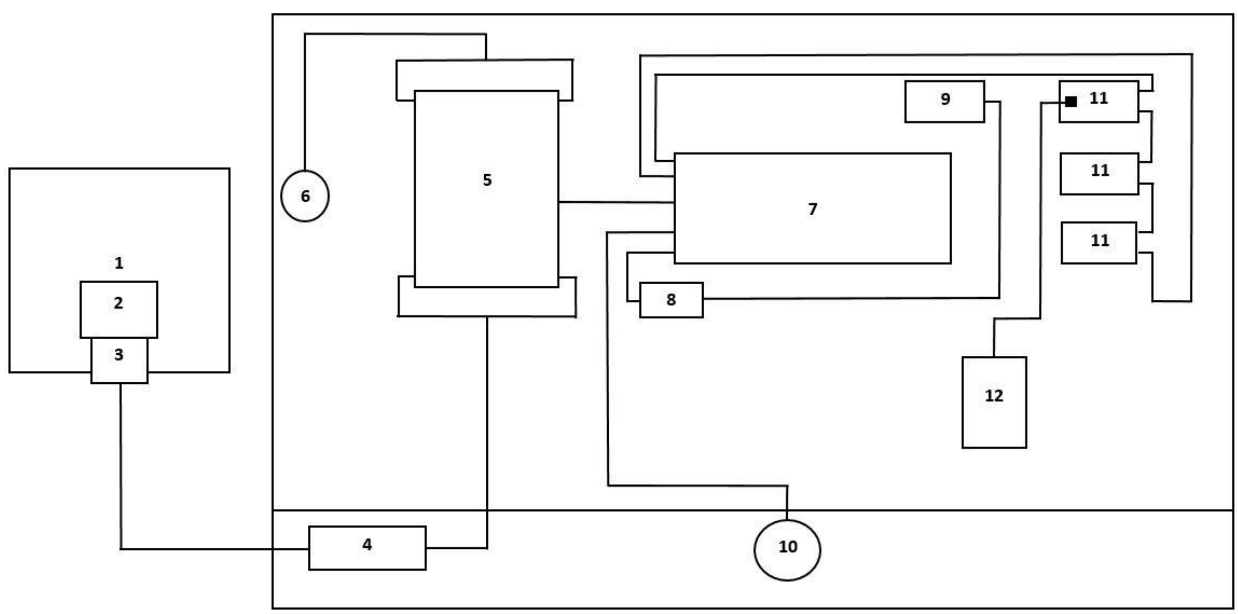


Figure 1 - Ventilation Hood Test Setup (Photograph)

The test setup is shown in Figure 2 diagram, Figure 1 photo and described in the following paragraphs.

To begin with, Figure 2 shows the layout of the ventilation hood from a top view with the key components shown. Testing was done inside the ventilation hood due to it constantly replacing the air inside of it, thus disposing of any hydrogen gas that might have leaked in a safe manner.

The first component in the test layout was the hydrogen gas tank (1), located to the left and outside of the ventilation hood. On top of the tank was a hand valve; when the valve was turned it released the gas. Attached to the valve output was the pressure regulator (2) and on the other end of the regulator was a “T” shaped fitting. Attached to the “T” fitting was the pressure gauge (3) and opposite to it was the tubing that continued the flow of hydrogen to the input side of the flow meter (4). Tubing was attached to the output side of the flow meter then connected to a “Y” fitting to split into two tubes. These two tubes were connected to the two gas supply inputs of the HFCS (5). On the other (output) side of the HFCS were two tubes that allowed distilled water, made by the HFCS, to exit properly into the water collection pan (6). Electrical power produced by the HFCS, was then supplied to the HFCC (7) by a cable and from there the controller distributed power to other components; i.e., the hydrogen leak sensor, and flow meter. Connected to the HFCC was the hydrogen leak sensor (8), which served as a safety device alerting us if the hydrogen gas concentration in the air was above normal. Although the hydrogen sensor was connected to the HFCC, it was also connected to the accessory battery (9). This was to make sure the hydrogen sensor had continuous power even if the HFCS was not supplying power to the system. The emergency stop button (10) was connected to the HFCC and served the purpose of turning off the HFCS in the event of a potential hazard for the team or the components. Connected to the HFCS electrical output were the load resistors (11) that were configured in order to provide the desired resistive load. The last component was the digital multimeter/thermometer (12). This component was used to verify the resistance from the individual resistors, the resistors in their testing configurations (see *Appendix B*), and to measure the surface temperature of the resistors at different output power levels.



1 - Hydrogen Gas Tank	2 - Pressure Regulator	3 - Pressure Gauge
4 - Pressure Regulator	5 - HFCS	6 - H2O Collector
7 - HFCC	8 - Hydrogen Leak Sensor	9 - Accessory Battery
10 - Emergency Stop Button	11 - Load Resistors	12 - Multimeter/ Thermometer

Figure 2 - Testing Configuration

Test Procedures

To begin testing, we first set up the resistors to the resistance configuration needed for each different load test as shown in Table 2 below and in *Appendix B: Load Resistors Configuration*.

Resistor Loads (Ω = ohm) and Average Power Output (W = watts)		
23.8 Ω = 87 W	16 Ω = 125 W	12 Ω = 164 W
8 Ω = 214 W	4.15 Ω = 401 W	2.85 Ω = 553 W
1.85 Ω = 867 W		

Table 2 - Hydrogen Fuel Cell Stack Average Power Output by Resistor Load

For example, we began testing at 23.8 ohms resistive load with the resistors connected according to *Appendix B: Diagram 1 - Load Resistor Configuration for 23.8 ohms.* We checked the resistance using the multimeter to make sure the configuration was correct and the wires had good connection.

After that, we set the pressure regulator to provide hydrogen gas to the HFCS within its specified input range of 7.25 psi to 9.25 psi in increments of 0.25 psi as shown in *Table 3* below.

Test Gas Pressure Ratings (psi = pounds per square inch)			
7.25 psi	7.5 psi	7.75 psi	8.0 psi
8.25 psi	8.5 psi	8.75 psi	9 psi
9.25 psi			

Table 3 - Hydrogen Gas Test Pressure for Hydrogen Fuel Cell Stack

After the pressure was set, we then turned on the flow meter. We then pressed and held the on/off button to start up the HFCS system. We double-checked that the pressure was set correctly and the fuel usage (liters/min or L/min) was being displayed on the flow meter. The HFCS output voltage and current was also displayed on the flow meter's LCD screen. Using the voltage (volts) and current (amps) readings we multiplied them together to calculate the output power (watts) delivered by the HFCS to the load resistors. Then, we divided the output power (watts or W) by the fuel usage (liters/min) in order to calculate the fuel efficiency (W/L/min) of the HFCS. We recorded our results on a spreadsheet (see *Appendix C - Test Results*). We then turned the knob to the next pressure value (see *Table 3 - Hydrogen Gas Test Pressure for Hydrogen Fuel Cell Stack*). In the meantime, we monitored the temperature of the resistors to make sure their temperature didn't exceed 300 degrees Fahrenheit. We repeated this process starting at 7.25 psi and increasing the hydrogen gas supply pressure by 0.25 psi increments until the highest allowable input gas pressure of 9.25 psi was reached. After we reached 9.25 psi we turned off the fuel cell, disconnected the resistors, and setup the next resistive load configuration (see *Appendix B - Load Resistor Configurations*).

Results and Discussion

Results

Complete test data is shown *Appendix C - Test Results*. This data was used to create graphs showing the fuel efficiency of the HFCS under the various input pressure and output load configurations (see *Fig. 3 – HFCS Fuel Efficiency vs. Input Gas Pressure)*. A description of the test results follows.

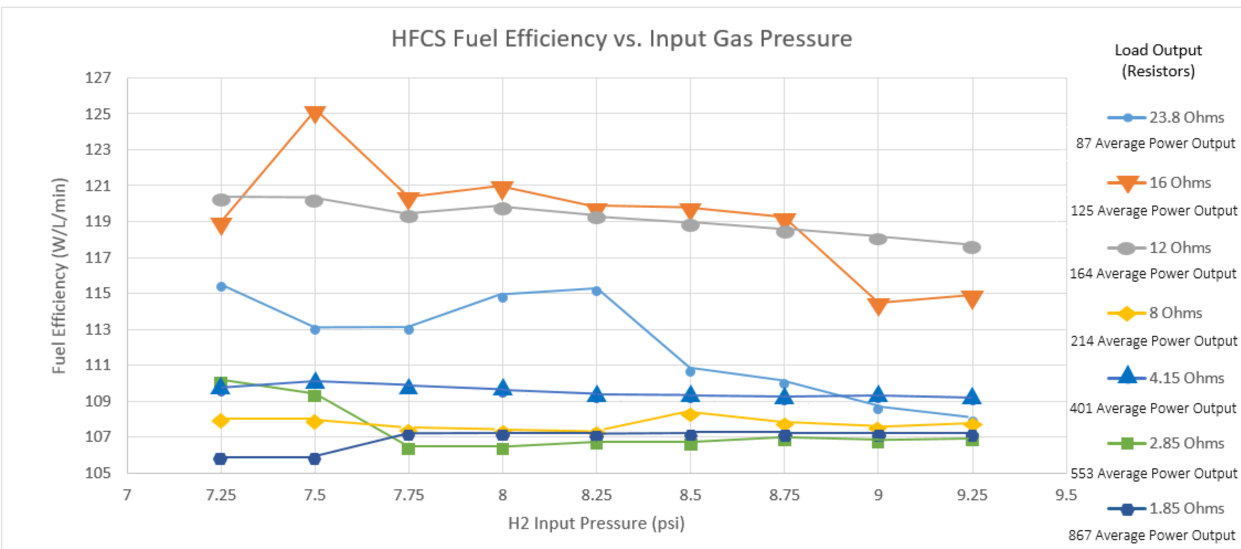


Figure 3 – HFCS Fuel Efficiency vs. Input Gas Pressure

On our first day of testing, we began with 23.8 ohms load resistance (see *Appendix C: Diagram 1 - Resistor Configuration for 23.8 Ohms*), producing an average output power of 87 W. At 7.25 psi the fuel cell produced the highest fuel efficiency of 115.36 (W/l/min) and decreased to 112.961 (W/L/min) at 7.5 and 7.75 psi. When we raised the hydrogen gas pressure from 7.75 psi to 8 psi the power jumped up rapidly to 114.76 (W/L/min). The levels increased by 0.37 from 8 to 8.25 psi to 115.129 (W/L/min). From 8.25 to 9.25 psi, fuel efficiency dropped steadily to its lowest value from 115.129 to 107.888 (W/L/min).

Next, we tested the hydrogen fuel cell with 16 ohms of load resistance (see *Appendix C: Diagram 2 - Resistor Configuration for 16 Ohms*), producing an average output power of 125 W. From 7.25 psi to 7.5 psi, fuel efficiency dramatically increased from 118.8 to 125.1 (W/L/min). From 7.5 psi to 7.75 (W/L/min) dropped down to 120.2 and by 8 psi the efficiency rose for the last time up 0.6 (W/L/min). At 8 to 8.75 psi the (W/L/min) gradually declined from 120.8 to 119.1. From 8.75 to 9 psi (W/L/min) drops from 119.1 to 114.4 and finally elevates again to 114.7 (W/L/min) at 9.25 psi. Then, at 12 ohms of resistance, (see *Appendix C: Diagram 3 - Resistor Configuration for 12 Ohms*), and an average output power of 164 W, fuel efficiency levels remained constant from 7.25 and 7.5 psi at 120.1 (W/L/min). From 7.5 to 9.25 psi the (W/L/min) went on a downwards trend to 117.6 (W/L/min). We noticed at 8 ohms of resistance (see *Appendix C: Diagram 4 - Resistor Configuration for 8 Ohms*), and an average output power of 214 W, fuel efficiency results decreased at 7.25 psi with 107.9 to 107.2 (W/L/min) at 8.25 psi. At 8.5 psi, fuel efficiency spikes up to 108.2 and drops back down again ending at 107.7 (W/L/min) at 9.25 psi.

In addition, minimal change occurred in fuel efficiency when we tested the fuel cell at 4.15 ohms of resistance (see *Appendix C: Diagram 5 - Resistor Configuration for 4.15 Ohms*) and an average output power of 401 W, from 7.25 psi at 109.556 (W/L/min) to 9.25 psi at 109.046 (W/L/min). Then, we reduced the resistance to 2.85 ohms (see *Appendix C: Diagram 6 - Resistor Configuration for 2.85 Ohms*) producing an average output power of 553 W. At this configuration the fuel efficiency at 7.25 psi was 110.048 and 109.273 (W/L/min) at 7.5 psi. Fuel efficiency levels remained fairly consistent from 7.75 to 9.25 psi at 106.326 to 106.924 (W/L/min) with slight change in between.

On our final day of testing we tested at 1.85 ohms of resistance (see *Appendix C: Diagram 7 - Resistor Configuration for 1.85 Ohms*) and an average output power of 867 W. The fuel efficiency at 7.25 and 7.5 psi (W/L/min) remained constant at 105.783. To our surprise, the efficiency increased then remained level at exactly 107.089 (W/L/min) from 7.75 through 9.25 psi. Overall testing at the smaller load resistances of 8, 4.15, 2.85, and 1.85 ohms and higher output powers (214 W to 867W) resulted in fairly constant fuel efficiency values from 7.75 to 9.25 psi.

Discussion

Over the course of our project, we overcame obstacles that were essential for us to be successful in our research. In the beginning of our assignment for this summer, most of the team members had little or no knowledge of how the Hydrogen Fuel Cell Stack worked. During the first two weeks of the project, we familiarized ourselves with the different parts of the HFCS by laying out all the component on a table such as the Hydrogen fuel cell controller, DC/DC converter, and the HFCS. All the members gained hands on experience on how to connect the entire system before we began testing. Then, we created electrical and block diagrams to safely test the fuel cell system according to dimensions of the hydrogen fuel cell vehicle. Therefore, we made a case holder for the hydrogen tank and a base to put all the components on for safety measures and to have a composed electrical system model.

In the meantime, we faced horrendous time delays that risked the completion of our project. We had purchased a Flow Meter that was from Switzerland. Once it finally arrived, when we opened the package and realized that the compression fittings (tubing connections of the flow meter) were not included in the packaging. Without those parts, we couldn't begin testing. We did extensive research on the companies who are associated with the flow meter to find these rare compression fittings. In the end we found the right compression fittings and began testing right away.

Lessons learned from this project include purchasing items in the United States rather than internationally. Secondly, it is important to confirm that you have all the components needed for the project before testing to avoid any future setbacks that may occur. Finally, you must leave room for error and be conscious of time delays to help overcome tedious obstacles.

Conclusions

Based on the findings from testing the HFCS with different output loads and varying input hydrogen gas pressures we discovered two things. First, by increasing the load (i.e., with a smaller load resistance resulting in higher output power) the fuel efficiency of the HFCS decreased in most cases. In other words, the fuel efficiency of the HFCS is higher at low output power levels and lower at high output power levels in general. Second, the fuel efficiency at higher output power levels did not vary much from the lowest to the highest input gas pressures applied. In fact, increasing the pressure of the hydrogen gas supplied to the HFCS above 7.75 psi had little to no effect on its fuel efficiency at the four highest power output levels (214, 401, 553, 867 W). Third, for the three lowest power output levels (87, 125, 164W) increasing the gas pressure caused the efficiency of the HFCS to generally decline especially above 8.25 psi input gas pressure.

The higher fuel efficiencies of the HFCS occurred when both the input gas pressure and power output were low. The highest fuel efficiency measured was 125.1 W/L/min at 7.5 psi input gas pressure and 129.5 watts output power. The lower fuel efficiencies of the HFCS occurred when the power output was high. The lowest fuel efficiency measured was 105.8 W/L/min, which occurred when the output power was 867.4 watts and the input hydrogen gas pressure was 7.25 psi or 7.5 psi.

The test results should be beneficial in reaching optimum hydrogen fuel cell vehicle performance in the Shell Eco-Marathon competition by knowing what hydrogen gas pressure supplied to the HFCS will result in the best fuel efficiency.

Future Testing

Despite having gathered all the necessary information needed and testing going as planned, there are still various ways to improve future testing and different topics to research utilizing the HFCS. Our research consisted of figuring out how the HFCS would perform under different loads and gas pressure levels. That information helped us in preparation for the Shell Eco Marathon competition. However, the data found can be improved and has potential to be more beneficial to the SAC Motorsport Team in two ways. First, the load on the HFCS or resistors, can be replaced with an electric hub motor (wheel with a motor pre-attached on its hub). This would yield beneficial information for the competition since it's what will be used for the competition. In addition, the majority of the components and procedures that were used for this SURP project can be used for load testing a hub motor. Secondly, not only can the HFCS be load tested with a hub motor, but the motor itself can be load tested. To do this the motor would need a resistance or weight applied to it, helping to simulate it being on the ground and working as intended. Both of these types of tests are planned to occur in the near future as a hub motor has already been purchased and will soon be ready for testing with the HFCS.

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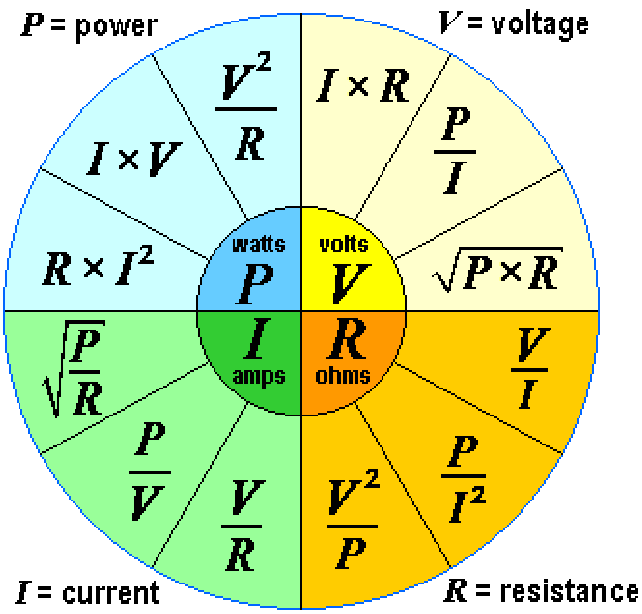
Appendix

Appendix A - Electrical Formulas



Appendix B - Load Resistor Configurations

Note: All resistors are 8Ω and rate at 200W maximum. Diagrams show expected power dissipation in each resistor and expected currents.

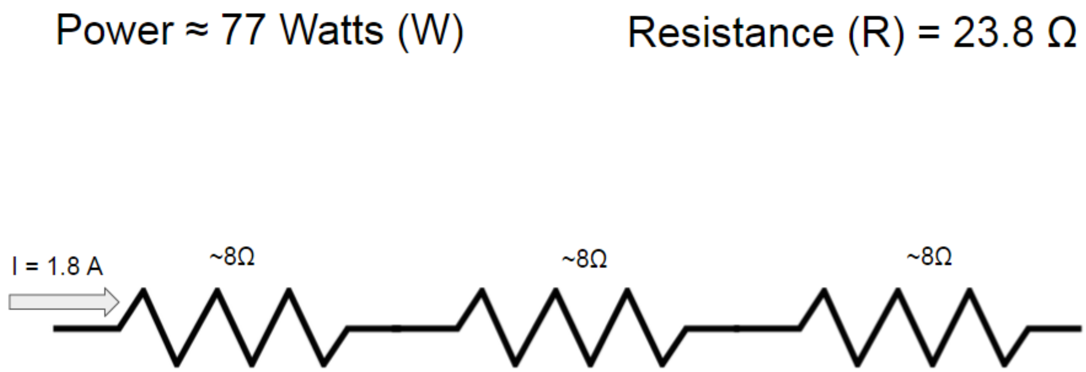


Diagram 1 - Load Resistor Configuration for 23.8 ohms

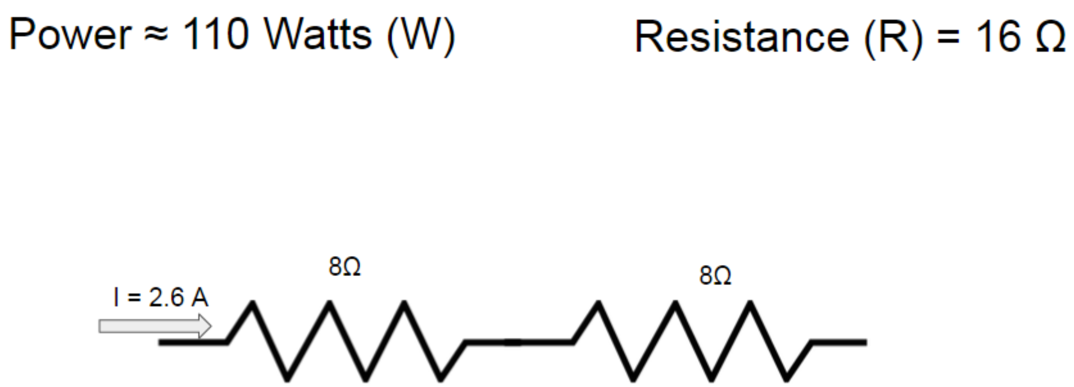


Diagram 2 - Load Resistor Configuration for 16 ohms

Appendix B - Load Resistor Configurations (continued)

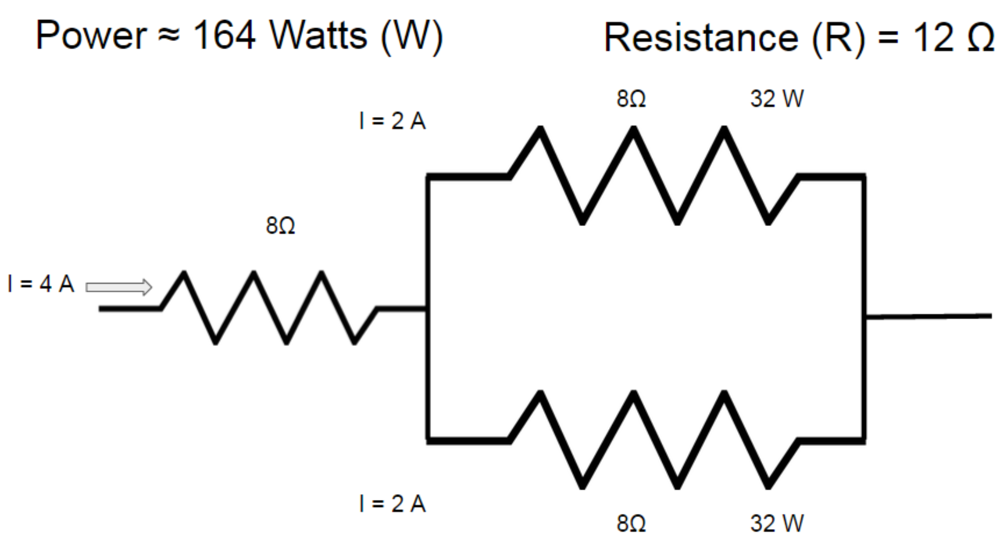


Diagram 3 - Load Resistor Configuration for 12 ohms

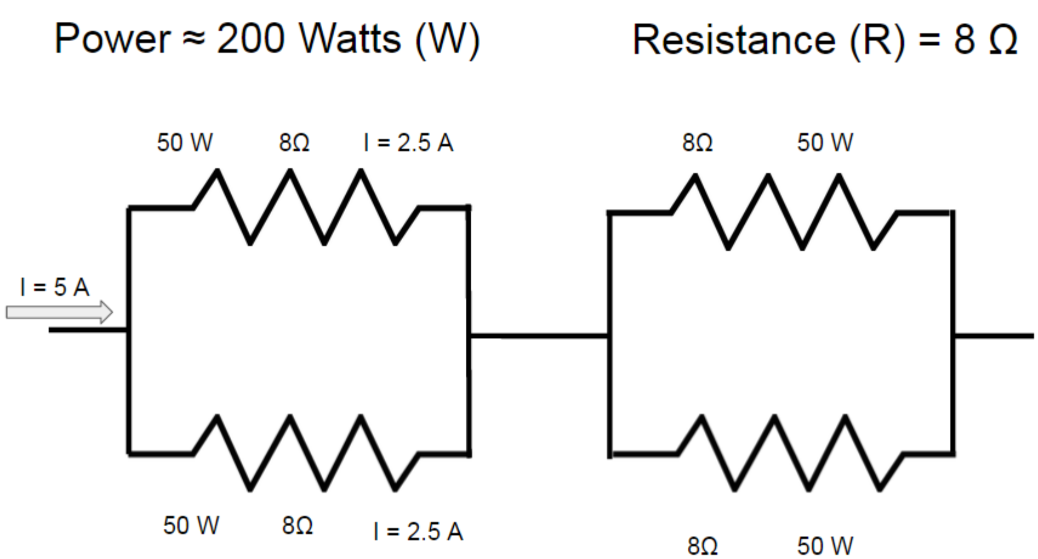


Diagram 4 - Load Resistor Configuration for 8 ohms

Appendix B - Load Resistor Configurations (continued)

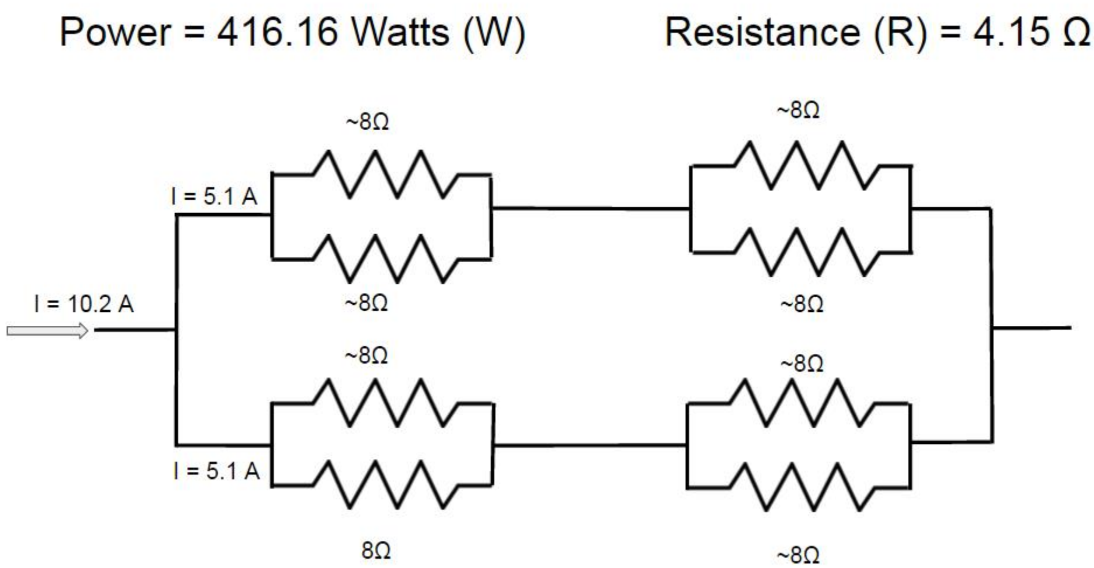


Diagram 5 - Load Resistor Configuration for 4.15 ohms

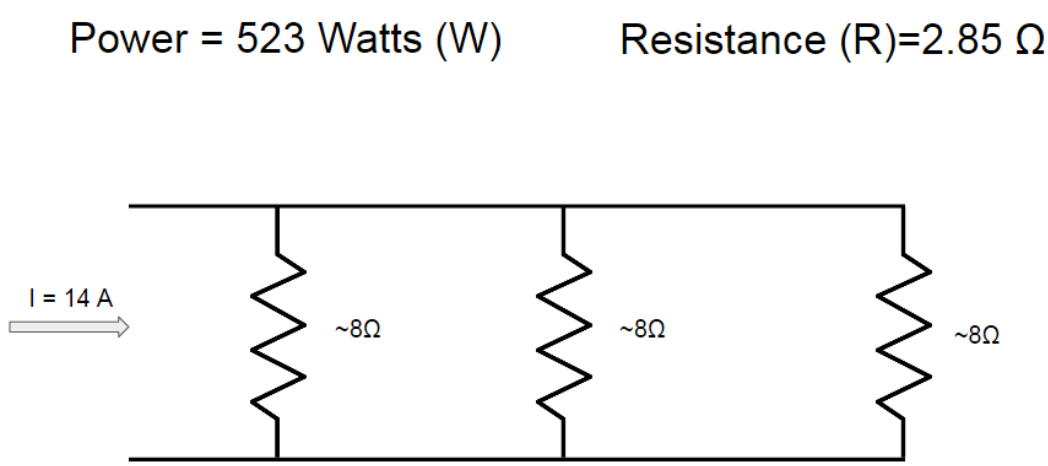


Diagram 6 - Load Resistor Configuration for 2.85 ohms

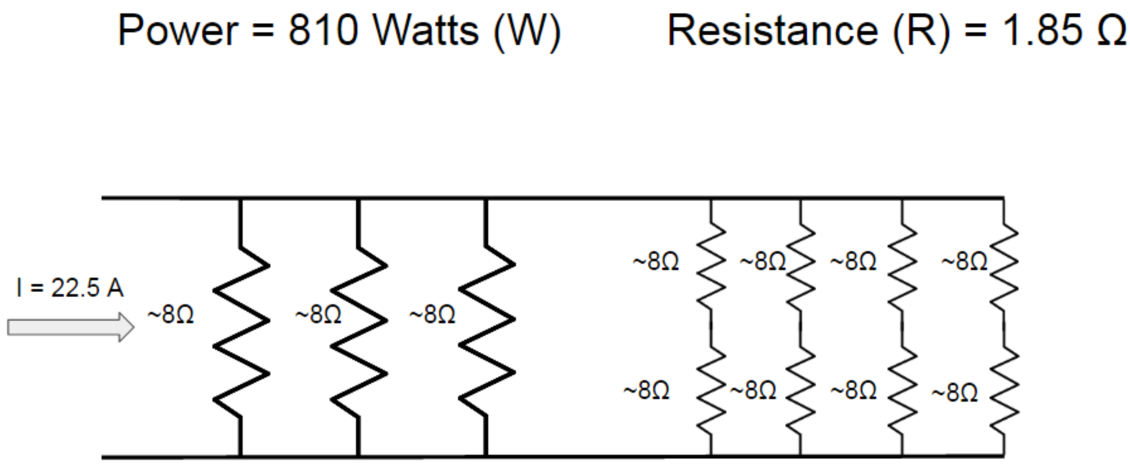


Diagram 7 - Load Resistor Configuration for 1.85 ohms

Appendix C - Test Results

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	86.52	41.2	2.1	23.8	7.25	0.75	3	115.360
Test 2	86.415	41.15	2.1	23.8	7.5	0.765	3	112.961
Test 3	86.415	41.15	2.1	23.8	7.75	0.765	3	112.961
Test 4	88.365	41.1	2.15	23.8	8	0.77	3	114.760
Test 5	89.225	41.5	2.15	23.8	8.25	0.775	3	115.129
Test 6	86.31	41.1	2.1	23.8	8.5	0.78	3	110.654
Test 7	86.31	41.1	2.1	23.8	8.75	0.785	3	109.949
Test 8	86.31	41.1	2.1	23.8	9	0.795	3	108.566
Test 9	86.31	41.1	2.1	23.8	9.25	0.8	3	107.888

Diagram 1 - Resistor Configuration for 23.8 Ohms

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	123	41	3	16	7.25	1.035	2	118.841
Test 2	129.465	41.1	3.15	16	7.5	1.035	2	125.087
Test 3	123.83	40.6	3.05	16	7.75	1.03	2	120.223
Test 4	125.05	41	3.05	16	8	1.035	2	120.821
Test 5	123.83	40.6	3.05	16	8.25	1.035	2	119.643
Test 6	123.83	40.6	3.05	16	8.5	1.035	2	119.643
Test 7	123.83	40.6	3.05	16	8.75	1.04	2	119.067
Test 8	123.525	40.5	3.05	16	9	1.08	2	114.375
Test 9	125.05	41	3.05	16	9.25	1.09	2	114.725

Diagram 2 - Resistor Configuration for 16 Ohms

Appendix C - Test Results (continued)

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	164	41	4	12	7.25	1.365	3	120.147
Test 2	164	41	4	12	7.5	1.365	3	120.147
Test 3	164	41	4	12	7.75	1.375	3	119.273
Test 4	164	41	4	12	8	1.37	3	119.708
Test 5	164	41	4	12	8.25	1.375	3	119.273
Test 6	164	41	4	12	8.5	1.38	3	118.841
Test 7	164	41	4	12	8.75	1.385	3	118.412
Test 8	164	41	4	12	9	1.39	3	117.986
Test 9	164	41	4	12	9.25	1.395	3	117.563

Diagram 3 - Resistor Configuration for 12 Ohms

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	212.53	40.1	5.3	8	7.25	1.97	4	107.883
Test 2	212.53	40.1	5.3	8	7.5	1.97	4	107.883
Test 3	212.53	40.1	5.3	8	7.75	1.98	4	107.338
Test 4	212.795	40.15	5.3	8	8	1.985	4	107.202
Test 5	212.795	40.15	5.3	8	8.25	1.985	4	107.202
Test 6	214.8025	40.15	5.35	8	8.5	1.985	4	108.213
Test 7	214.8025	40.15	5.35	8	8.75	1.995	4	107.670
Test 8	214.8025	40.15	5.35	8	9	2	4	107.401
Test 9	214.8025	40.15	5.35	8	9.25	1.995	4	107.670

Diagram 4 - Resistor Configuration for 8 Ohms

Appendix C - Test Results (continued)

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	399.33	39.15	10.2	4.15	7.25	3.645	8	109.556
Test 2	401.2875	39.15	10.25	4.15	7.5	3.65	8	109.942
Test 3	401.2875	39.15	10.25	4.15	7.75	3.66	8	109.641
Test 4	401.2875	39.15	10.25	4.15	8	3.665	8	109.492
Test 5	401.2875	39.15	10.25	4.15	8.25	3.675	8	109.194
Test 6	401.2875	39.15	10.25	4.15	8.5	3.675	8	109.194
Test 7	401.2875	39.15	10.25	4.15	8.75	3.68	8	109.046
Test 8	401.2875	39.15	10.25	4.15	9	3.675	8	109.194
Test 9	401.2875	39.15	10.25	4.15	9.25	3.68	8	109.046

Diagram 5 - Resistor Configuration for 4.15 Ohms

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	572.25	38.15	15	2.85	7.25	5.2	3	110.048
Test 2	571.5	38.1	15	2.85	7.5	5.23	3	109.273
Test 3	548.64	38.1	14.4	2.85	7.75	5.16	3	106.326
Test 4	548.64	38.1	14.4	2.85	8	5.16	3	106.326
Test 5	548.64	38.1	14.4	2.85	8.25	5.14	3	106.739
Test 6	546.735	38.1	14.35	2.85	8.5	5.13	3	106.576
Test 7	547.4525	38.15	14.35	2.85	8.75	5.12	3	106.924
Test 8	546.735	38.1	14.35	2.85	9	5.12	3	106.784
Test 9	547.4525	38.15	14.35	2.85	9.25	5.12	3	106.924

Diagram 6 - Resistor Configuration for 2.85 Ohms

Appendix C - Test Results (continued)

	Watts (W)	Volts (V)	Amps (A)	Ohms (RL)	Pressure	ls/min	Load (Resistors)	W/L/min
Test 1	867.42	36.6	23.7	1.85	7.25	8.2	5	105.783
Test 2	867.42	36.6	23.7	1.85	7.5	8.2	5	105.783
Test 3	867.42	36.6	23.7	1.85	7.75	8.1	5	107.089
Test 4	867.42	36.6	23.7	1.85	8	8.1	5	107.089
Test 5	867.42	36.6	23.7	1.85	8.25	8.1	5	107.089
Test 6	867.42	36.6	23.7	1.85	8.5	8.1	5	107.089
Test 7	867.42	36.6	23.7	1.85	8.75	8.1	5	107.089
Test 8	867.42	36.6	23.7	1.85	9	8.1	5	107.089
Test 9	867.42	36.6	23.7	1.85	9.25	8.1	5	107.089

Diagram 7 - Resistor Configuration for 1.85 Ohms