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14. ABSTRACT
The project proposed to carry out two studies aimed at modeling and optimizing hydrogen fuel cells systems: i) the optimization of fuel cell structure for maximum power density, and ii) regenerative fuel cell systems. We believe the two areas are of great relevance to AFOSR's mission. For that the project achieved: the optimization of SOFC and PEMFC internal structure and external shape under a volume constraint; an initial set of subcomponent models for regenerative, renewable fuel cell system (RFC); the integration of PEMFC into RFC systems were developed; power electronic component models, and energy storage models were developed and implemented; pilot synthesis of renewable fuel cell system computational model with initial parametric studies regarding performance and reliability trends were implemented through the constrution of a self-sustainable cabinet based on fuel cell technology and solar energy.

15. SUBJECT TERMS
Mathematical Models, Regenerative Fuel Cell System, Self-sustainable cabinet

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FINAL REPORT

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Contract/Grant Title: Modeling and optimization of renewable and hybrid fuel cell systems for space power and propulsion

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1. General Progress

The project had the following original milestones, products and deliverables. For the sake of brevity, the achievements are summarized after each of the originally established milestones.

Milestones

1st year: Optimized SOFC internal structure and external shape under volume constraint – study 1
Initial set of subcomponent models for regenerative, renewable fuel cell system(s) – study 2

Comments: 1. The internal flow structure of a unitary SOFC was optimized using modeling methods to achieve maximum power output [1];

2. Initial studies on the individual components of a regenerative fuel cell system were performed, which lead to the resetting of the research strategy. Since SOFC commercial systems available are well over the project's budget, it was decided to proceed with the same objectives and goals but using a PEMFC regenerative system instead. This research group studied and published on the optimization and construction of such cells [2], and

3. A fully new concept of a solid-supported membrane-like alkaline fuel cell (AMFC) was also developed, and a first operational prototype, built with a semi-optimized structure presented a very promising performance.

2nd year: Integration of SOFC into RFC systems – studies 1 and 2 Power electronic component models, develop energy storage model – study 2

Comment: 1. On April 10, 2008, Mr. James Fillerup, and Dr. Mitat Birkan visited the Fuel Cell Laboratory at UFPR (partially funded by this project), in Curitiba, PR, Brazil, and saw the initial progress of the project and a presentation with the expected outcomes from the UFPR research group. A general internal view of the laboratory is seen in Fig. 1, and

Figura 1 – General internal view of the Fuel Cells laboratory at UFPR.

2. As planned in the original project, in the second year, the group elaborated the design of the integration of the PEMFC (instead of an SOFC) into RFC systems. The design consisted of a solar photovoltaic panel coupled with a sun tracer device, with a power stabilizer used to connect the array to 4 batteries in series (48 V), which are charged continuously. The batteries then feed an electrolyzer, which fills up an H_2 reservoir that feeds a NEXA 1.2 kW PEMFC stack. The water produced in the stack is collected and condensed to return for utilization in the electrolyzer, in this way minimizing water consumption. The implementation of the design started with the construction of a cabinet with the solar panel, sun tracer and batteries, which operated in a self-sustainable mode, all funded by a brazilian company partner (NILKO Metalurgia Ltda). The electrolyzer was purchased by the project from Proton Energy (USA).

3rd year: Pilot synthesis of renewable fuel cell system computational model with initial parametric studies regarding performance and reliability trends – study 2

Comments: 1. As stated earlier, a fully new concept of a solid-supported membrane-like alkaline fuel cell (AMFC) was developed, and a first operational prototype, built with a semi-optimized structure presented a very promising performance in the laboratory. A photo of the prototype in the laboratory is shown on Fig. 2;

2. The prototype presents a lamelar structure, in which the liquid electrolyte (KOH solution) is supported by a porous cellulosis membrane;

3. The prototype has been patented in the US [3] and is at an experimental characterization stage. A mathematical model is under development in order to perform a numerical simulation and optimization study of the AMFC after the model experimental validation;

4. The first prototype has shown a better performance than commercially available PEMFC's of similar size. Figure 3 shows some of the preliminary results in comparison of an existing commercial PEMFC of similar size to the AMFC prototype, and

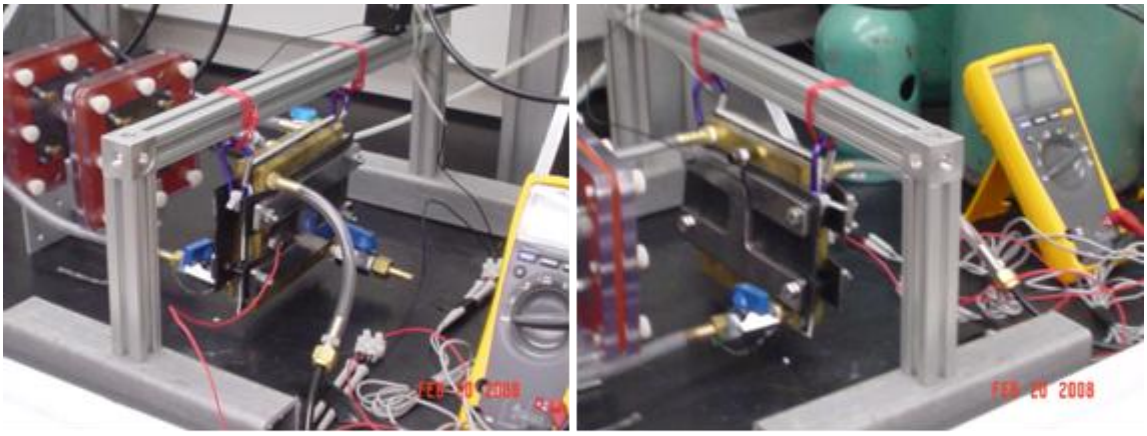

Figure 2 – Prototype of a Alkaline Membrane Fuel Cell (AMFC) patented in the US [3].

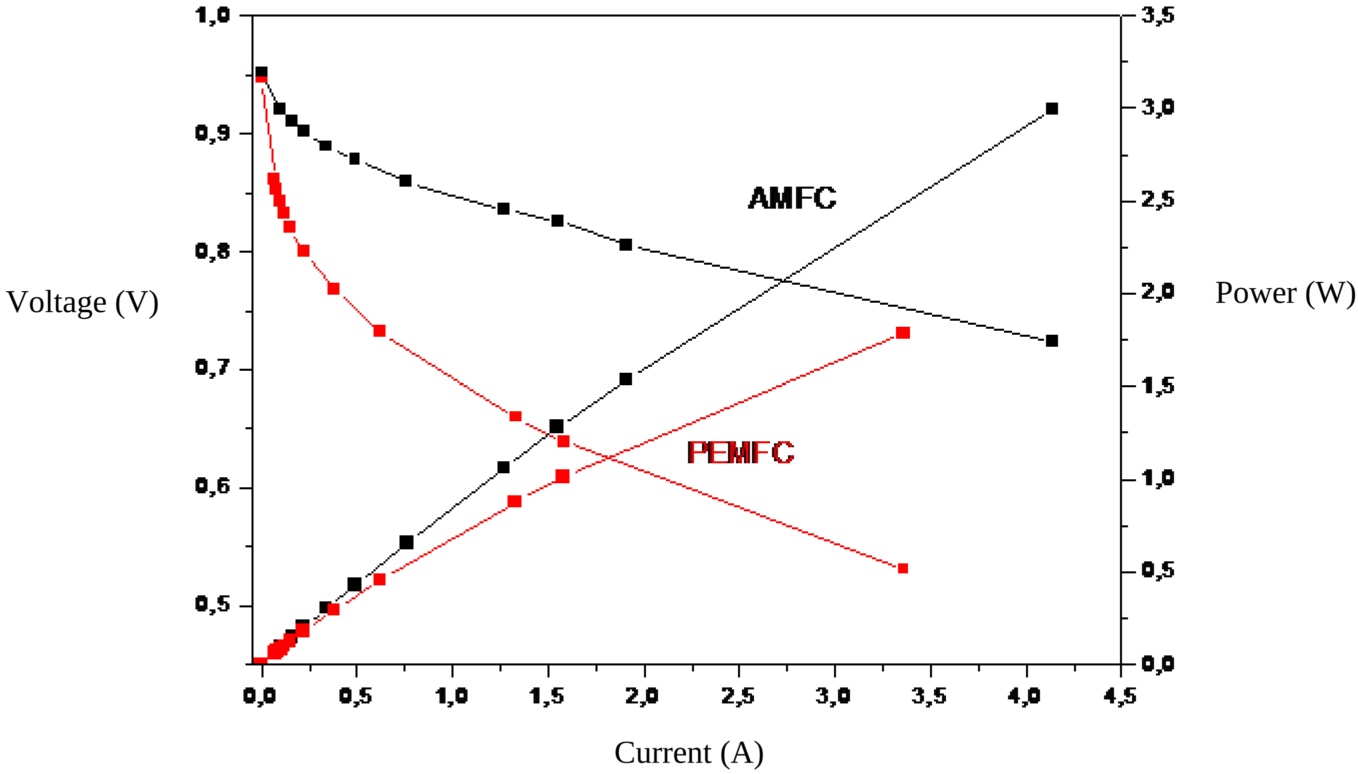

Figura 3 – Comparison between Polarization and Power curves of the AMFC prototype and of a commercial PEMFC, manufactured by Schatz Energy Research Center, SERC, Humboldt State University, Arcata, California, Tel: (707) 826-4345, Fax: (707) 826-4347, E-mail: serc@humboldt.edu.

5. After the design of the integration of the PEMFC into RFC systems, its implementation continued in the 3rd year with the construction of a cabinet with the solar panel, sun tracer and batteries, all funded by a brazilian company partner (NILKO Metalurgia Ltda). The electrolyzer was purchased by the project from Proton Energy (USA) and adapted to the system with a DC-AC converter. A 1 year no cost extension was requested and granted, so that the system could be finished and tested operating in a self-sustainable mode. A PEMFC mathematical model was written and experimentally validated to simulate the project's PEM RFC [4]. A new Fuel Cell laboratory was built at UFPR partially funded by the project, as shown in Fig. 1. In the 4th year, Prof. Ordonez from FSU visited UFPR (May 2010) leading the construction of the prototype. The prototype implementation is described in detail in the text that follows.

Products and Deliverables

1st year: Year report with optimized SOFC internal structure and external shape

2nd year: Year report and pilot software of subcomponent models for regenerative, renewable fuel cell system

3rd year: Year report regarding the initial renewable fuel cell system synthesis "trades" associated with PEM/solid oxide, as well as dedicated/reversible, electrochemical cell options, and copies of all resulting publications.

Comments: 1. All reports were sent to AFOSR in due time.

2. The project was granted a 1 year no cost extension in July 2009. Therefore a final report was scheduled to be sent only on 14 Nov 2010.

2. PROTOTYPE DESCRIPTION

Title: Self-Sustainable Cabinet Based on Fuel Cell Technology and Solar Energy

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ABSTRACT

In recent years, there has been intensive research on clean and renewable energy production. Two main reasons have been pointed out: pollution caused by oil based fuels consumption and their depletion, which increases their production costs. Fuel Cells have shown to be a clean and renewable energy source, which turns them into a promising solution, although technology hurdles still need to be overcome. Fuel Cells produce electricity, water and heat consuming hydrogen and pure oxygen or air. This prototype combines different components to produce a self-sustainable fuel cells technology based cabinet for energy production, which is a Regenerative Fuel Cell System (RFC) with potential for space applications. The system contains: a photovoltaic panel, a charge controller, 4 batteries, a DC/AC current inverter, a fuel cell stack, an electrolyser, a hydrogen storage bottle, and a DC/DC voltage controller. The photovoltaic panel charges the batteries, while the charge controller controls the batteries loading. Batteries are connected to a DC/AC inverter. The inverter is connected to an electrolyser (Hogen GC 600) which splits the water molecule into hydrogen and oxygen molecules. The produced hydrogen supplies the fuel cell stack and the oxygen is released directly to the atmosphere. When energy is not required by the load, hydrogen is stored in the hydrogen bottle for later comsumption on demand. The fuel cell stack power production feeds a load through a DC/DC voltage controller. The system proved to be efficient and capable to use two renewable energy sources (solar and fuel cell technology) in a self-sustainable cabinet. It has also been shown that equipments such as Electrolyser, Fuel Cell Stack and Photovoltaic panel can be fit together in order to produce energy. Therefore, a Fuel Cells Regenerative System is hereby demonstrated feasible and a new, clean, renewable and regenerative energy production system.

KEY WORDS

Regenerative Fuel Cell System, Self-sustainable cabinet.

METHODOLOGY

Equipments

- Eletroliser Hogen GC600 (Proton Energy Systems Inc.®) [5]
- Charge Controller Xantrex 41XM
- Fuel Cell Stack NEXA 1.2 KW (Ballard Power Systems Inc.®) [6]
- 4 Ajax® Batteries 100 A.h
- MCE® Inverter DC/AC (12V to 110 V) MCE
- Datel® Converter DC/DC UHE-12/2500-Q48
- 24 V Power Source ELEKTRO – AUTOMATIK GmbH & Co.KG
- 6 Siemens® Circuit breakers 10 A
- 1 Siemens® Circuit Breaker 120 A
- 1 Nilko air-to-air 90 W/K door heat exchanger with 2 radial 50 W fans
- Photovoltaic Panel 195 W
- White Martins® Hydrogen Cylinder

The system

The Photovoltaic Panel under sun incidence charges the batteries. This charging is controlled by the Xantrex equipment.

There are several different operating possibilities in the system, which will depend on the combination of the following parameters: batteries charge, hydrogen cylinder pressure, and sun incidence. All the different working possibilities are a product of the combination of the positions on and off (closed and opened) of the 7 circuit breakers in the system (abbreviated as S1, S2, S3, S4, S5, S6 and S7). The system's layout is seen in the Fig. 4.

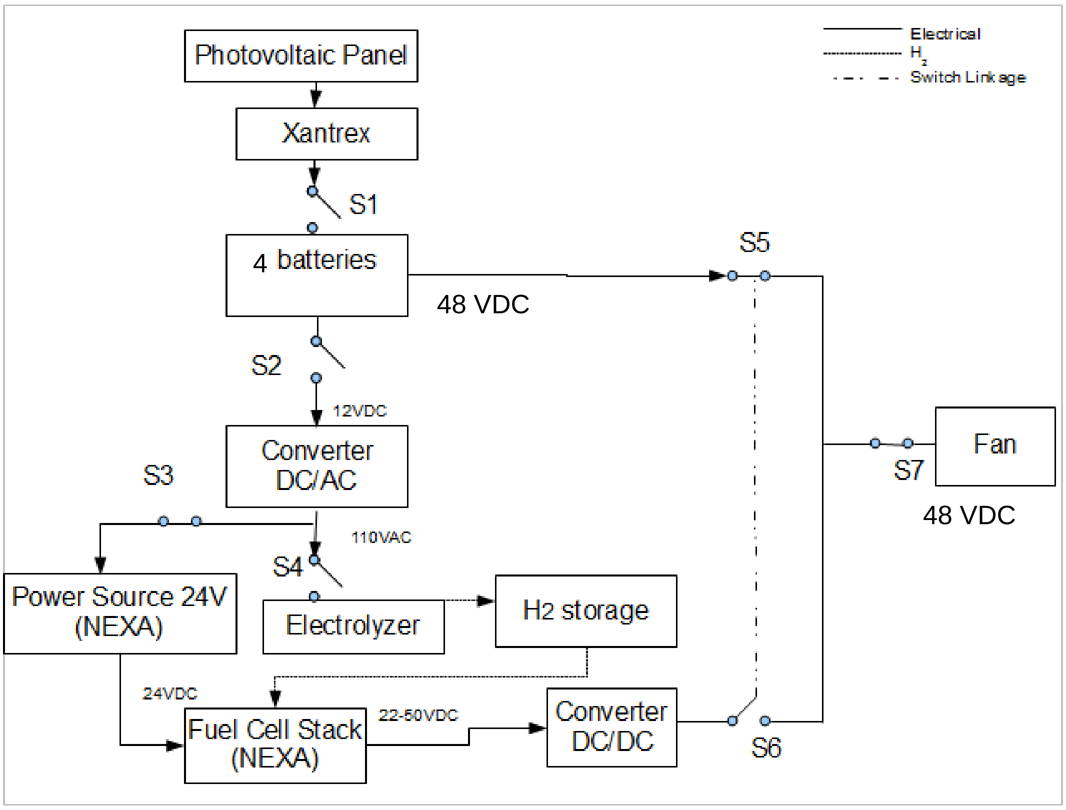

Figure 4 – System's Layout.

The discussion starts with the operating regimes under sun incidence.

The first working possibility is when there is sun light, the batteries are fully charged and the hydrogen cylinder pressure is acceptable (inside the interval of 80 and 200 psi). In this case the fan will be fed by the electric energy produced by the NEXA Fuel Stack. Only S1, S4 and S5 will be opened while S2, S3, S6 and S7 will be closed.

The second possibility is when the hydrogen pressure is below the lower limit (80 psi), there is sun light and the batteries voltage is above 12.5V. Then the electrolyser produces hydrogen that reloads the cylinder while the batteries feed the fan. The electrolyser is fed by the batteries, but the first one needs 110V alternating current to work, as the batteries produce 12V direct current, therefore it is necessary the presence of the inverter. In this case S1, S3 and S6 will be opened while S2, S4, S5 and S7 will be closed.

Other possibility is when the batteries voltage is critical (i.e., between 12.5 and 11.5 V), the hydrogen cylinder pressure is acceptable and there is sun light, then the Xantrex charges the batteries and the NEXA Stack feeds the fan. Then S1, S2, S3, S6 and S7 will be closed and only S4 and S5 will be opened.

Another possibility is when the charge level of the batteries is not below 11.5 V, there is sun light and the hydrogen cylinder pressure is below the lower limit. In this case, the Xantrex keeps recharging the batteries, both electrolyzer and fuel cell stack are not fed and the fan is fed by the batteries. When this happens, S1, S5 and S7 will be closed while the rest of the circuit breakers will be opened.

The last possibility is when the batteries voltage is below 11.5 V. When this happens, only the Xantrex charges the batteries and the rest of the system has to be off. Therefore only S1 will be closed and others circuit breakers will be opened.

A detail that cannot be forgotten is that every time the NEXA fuel cell stack feeds the fan, the DC/DC converter is needed, because of the fact that the NEXA's output is a function of the hydrogen's incoming pressure and the load required (in the present study the fan working load). In other words, the DC/DC converter converts the output stack voltage (22-50V) to the fan input voltage 48 V.

Another detail is that when hydrogen is needed for the fuel cell stack, a pressure regulator valve must be regulated to the required pressure (80 psi).

The different working possibilities can be summarized in Table 1:

Table 1 – Different operating regimes in the presence of sun incidence.

With sun incidence	
▪ Battery voltage is maximum (battery at full load)	▪ Battery voltage is critical (inside interval 11.5 - 12.5)
○ Hydrogen pressure is acceptable (inside interval 80 – 200 psi) S1: OPEN S2:CLOSED S3:CLOSED S4:OPEN S5:OPEN S6:CLOSED S7:CLOSED	○ Hydrogen pressure is acceptable (within interval 80 - 200 psi) S1:CLOSED S2:CLOSED S3:CLOSED S4:OPEN S5:OPEN S6:CLOSED S7:CLOSED
○ Hydrogen pressure below lower limit S1:OPEN S2: CLOSED S3:OPEN S4:CLOSED S5:CLOSED S6:OPEN S7:CLOSED	○ Hydrogen pressure below lower limit (80 psi) S1: CLOSED S2:OPEN S3:OPEN S4:OPEN S5:CLOSED S6:OPEN S7:CLOSED
▪ Battery voltage below minimum	
S1:CLOSED S2, 3,4,5,6,7: OPEN	

In the absence of sun incidence, the fan is powered by the fuel cell stack until the hydrogen storage bottle pressure level drops below 80 psi. Upon hydrogen shortage, the batteries take over until the sun appears again, and the system enters the sun incidence mode, according to the previously discussed alternatives.

Hydrogen Storage

The hydrogen storage is one of the essential parts of the system and, due to its complexity, will be explained individually, out of the whole system. First of all, to guarantee the hydrogen's purity, it is necessary to create vacuum at the line where the hydrogen flows, inside the storage system. In order to do that a "Tecnal TE-068" Vacuum Bomb is used. The hydrogen's final storage is made in a cylinder with capacity of 0.007 m^3 (in water volume). The pressure inside reaches a maximum of 200 psi, due to the electrolyzer's capacity. To make sure that the H_2 does not return both to the vacuum bomb and the electrolyzer, check valves and block valves were installed along the line. This also guarantees that H_2 is not wasted in the process. For safety measures, safe fire valves were installed too, and, in order to measure the hydrogen pressure on the line, the same was done to a manometer. The storage line also serves to feed the Ballard stack with hydrogen. In the present case the fuel cell stack's working pressure is constant and set to 80 psi. The hydrogen's storage system is shown schematically in Fig. 5.

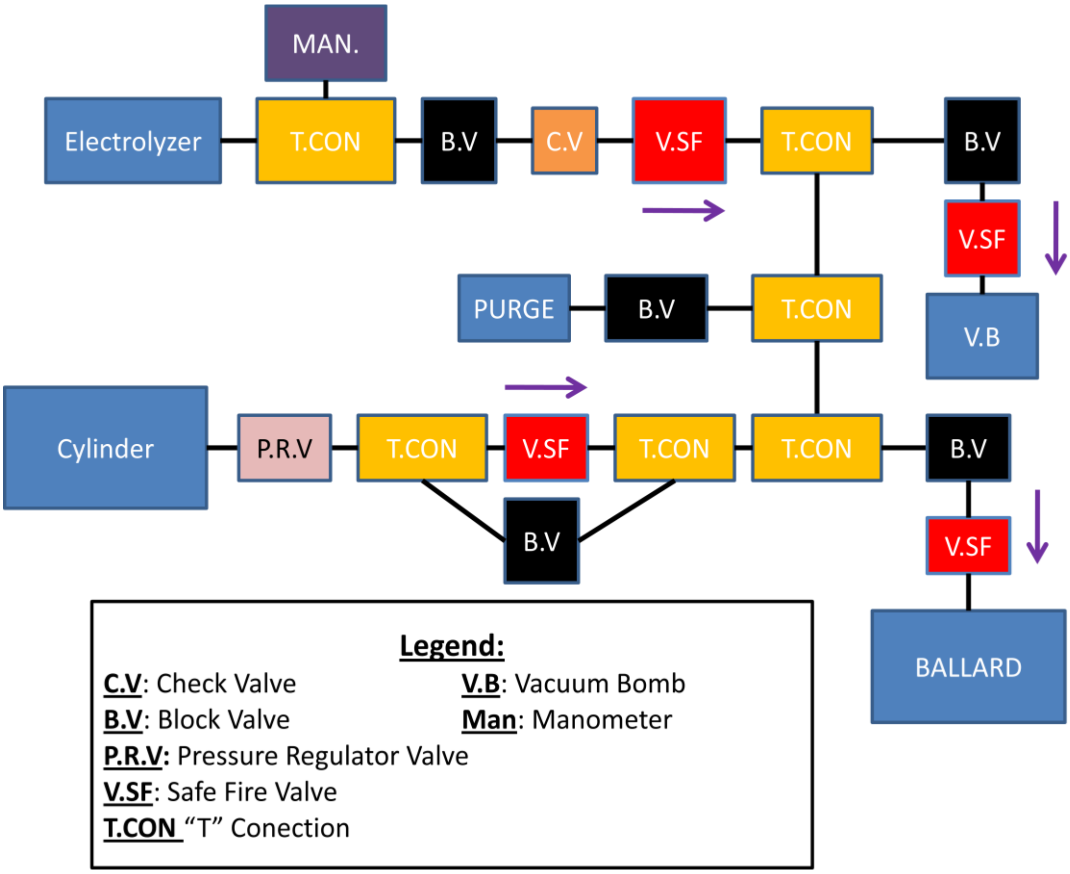

Figure 5 – Hydrogen's Storage Layout.

RESULTS

Solar Panel – Xantrex – Batteries

The Solar Panel charges the batteries as the Xantrex control the operation. In a day with high solar irradiation, by the time of 3 p.m, during the realization of a test, the batteries were charged by a voltage around 13.5V and a maximum current of 2.45A. The current ranged between 2.39V and 2.45V, as the solar light presence was more or less intense.

Batteries – Inverter – Electrolyser

In order to load the cylinder, the inverter's presence is necessary. The electrolyser needs to be fed by 110 VAC, as the batteries deliver 12VDC. To solve this, a DC/AC inverter (12V to 110V) was used. In the experiment, the batteries were placed in parallel and had initially 12.41V. In its warm-up (that takes approximately 64 minutes), the electrolyser consumed a current of 1.05A. After that, it began to produce hydrogen to its inner tank, until it reached the desired pressure (200 psi). This stage lasts 5 minutes and consumes a current of 3.24 A. The maintenance of the hydrogen flow also consumes 3.24 A and depends also on the load demand. The total test time was 78 minutes and the final voltage of the batteries was 11.99V.

Stack's Output – Converter – Fan's Input

When there is an acceptable hydrogen pressure inside the cylinder, the fans will be fed by the Ballard stack. However, this stack produces a voltage that varies between 22V and 50V. Therefore, a DC/DC converter with a 12V output is needed. In this experiment, the Ballard stack was supplied by a pressure of 100 psi, and provided enough energy to the fan's operation. The fan, in 30 minutes, consumed 12 liters of hydrogen at standard conditions of temperature and pressure, which means 0.4 liters per minute.

The current that passed by the fan was 0.34 A, while the current that was demanded by the Ballard was 0.14A (both direct currents). The cell's work voltage varied from 36.6 V to 36.7 V, as the voltage applied to the fan was 47.9V.

DISCUSSION

The results obtained after the conclusion of all experiments, in general, complied with the expectations showing the feasibility of the self-sustainable cabinet. The batteries' charge is enough to feed the fan, although the batteries charging (2.45A) is much lower than its discharging when they are feeding both the fan and the electrolyser. The batteries have also proven to provide enough energy for the electrolyser's warm up and filling up.

The HOGEN electroliser used in the first prototype releases the oxygen produced during the electrolysis to the atmosphere. For this reason, air or oxygen from an external source is required to feed the fuel cell stack. The water vapor produced by the fuel cell stack is also released to the atmosphere. Therefore, for space applications, the first prototype is not ready yet. For achieving that goal, an electrolyzer that allows the oxygen to be stored, and a fuel cell stack that allows the water vapor to be condensed and returned to the electrolyser for consumption will be required. Those items were not available commercially to this project. However, it is a matter of developing the specific items as described to produce a system that allows for a closed water cycle, with a minimum of make-up water, for space applications.

A general view of the constructed prototype is shown in Fig. 6. The UFPR team is currently working to allow for the system to work with a closed water cycle, and tests are scheduled to be performed before the end of the current year (2010).

CONCLUSIONS

The system has proved to work efficiently, therefore it has a great potential for future developments as renewable energy power souce. Therefore, the UFPR team believes that the project has accomplished all the original objectives.

Figure 6 – Self-sustainable cabinet with solar panel and sun tracer mounted on top. The batteries' compartment (left) and the hydrogen storage bottle (right).

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