RP-94-33

CATHODE AIR CONTROL OF A PEM FUEL CELL STACK OPERATING ON THE USABC DYNAMIC STRESS TEST

David H. Swan, Murali Arikara, Blake Dickinson and Manohar Prabhu
Institute of Transportation Studies
University of California
Davis, CA 95616

ABSTRACT

This paper presents experimental data on the performance of a proton exchange membrane (PEM) fuel cell system operating on the USABC Dynamic Stress Test (DST) as a function of cathode air flow rate and inlet pressure. The fuel cell system used was a Ballard Power Systems' 35 cell stack. The experiments were performed by operating the fuel cell stack on the DST with a pulse-width-modulated controller and simulating the operation of a variable output compressor with a mass flow controller and electronic back pressure regulator. Dynamic conditions reduce the fuel cell average efficiency. Air compressor control was found to be critical to maximize net efficiency.

INTRODUCTION

A fuel cell power plant is a complex group of systems that must dynamically operate to provide power. To meet the varying driving load conditions of an electric vehicle (EV), the fuel cell power plant must frequently go from an idle state to full power and return to idle. The rate of these changes and duration at each power level depends on the fuel cell size, the driving profile and the power system configuration (perhaps hybidized with a storage battery). The cathode air stoichiometry (S) and pressure (P) are difficult to maintain and optimize over the wide variety of operating conditions experienced in dynamic operation. It is anticipated that an EV fuel cell will use a variable output air compressor to optimally control S and P. The response time and control logic of the air compressor will affect net efficiency and power output. For background information, the reader is referred to a previous characterization of the same fuel cell stack under steady-state operating conditions[1]. Previous investigation of similar dynamic characteristics can be found in Oliveira et al[2], Dickinson et al[3] and a description of a fuel cell powered bus can be found in Howard and Greenhill[4]. This paper is the first in a planned series to investigate the dynamic response of fuel cells for transportation.

EXPERIMENTAL SETUP

The experimental setup consisted of the fuel cell stack, a stack instrumentation and support system (SISS) and a dynamic load bank, see Figure 1. The fuel cell system used was a Ballard Power System 35 cell stack with a 232 cm^2 of active area per cell, employing a Nafion-117 electrolyte membrane. Further information on this system can be found in reference 1. The SISS is a rolling cabinet designed and built at UC Davis to control and monitor a fuel cell stack. In this paper the SISS was primarily used to control cathode air supply and monitor the fuel cell performance. The dynamic load bank was a resistor bank connected to the fuel cell by a pulse-width-modulated controller. The load control was interfaced with the SISS and could be programmed for different load cycles. The SISS and load bank were set up and controlled by an IBM-compatible personal computer. Figure 1 shows the experimental setup used for the cathode air control of the dynamic load test.

The fuel cell stack was loaded according to the Dynamic Stress Test (DST) developed by the United States Advanced Battery Consortium (USABC) to evaluate advanced batteries under dynamic conditions[5]. The USABCs test cycles set a standard by which alternative power system technologies can also be compared to one another. However, since the fuel cell cannot accept the regenerative portions of the DST cycle, these were ignored. (See Figure 2.) The DST cycle peak discharge power point was set to 2400 Watts. This value represents a rate of discharge that can be achieved by the stack under all dynamic conditions. The average power over one DST cycle for the fuel cell stack is 360 Watts. This corresponds to an energy of 36 Watt hours per cycle.

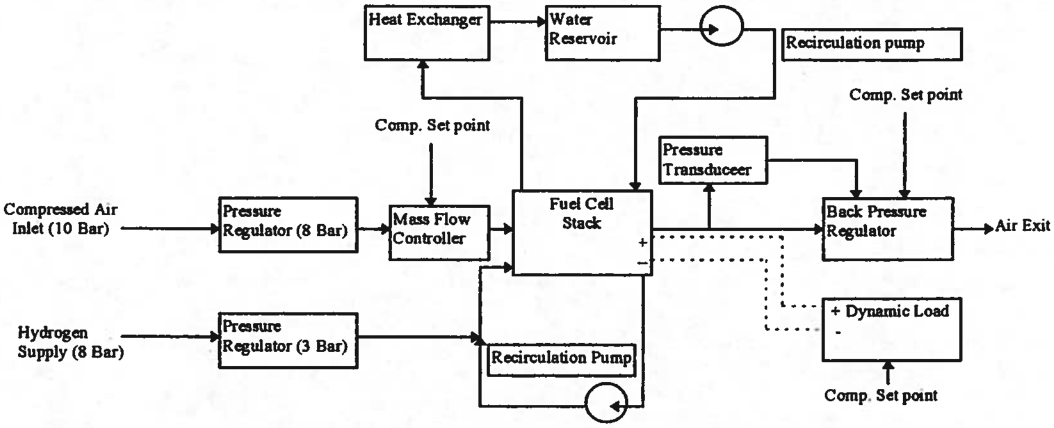


Figure 1. Schematic of Experimental Setup

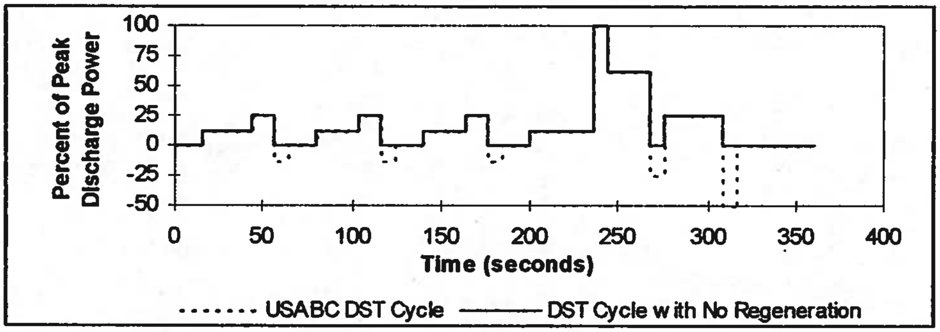


Figure 2. USABC Dynamic Stress Test

EXPERIMENTAL PROCEDURE

For the performance measurements of the fuel cell stack, five different cases were considered. The five cases were selected as a first approximation to determine the influence of dynamic operation on the fuel cell stack and the energy needs for cathode air compression. The first case was under steady state electrical load conditions. The following 4 cases were all under dynamic (DST) electrical load. The dynamic load cases explored the effect of varying the cathode air stoichiometry and the cathode exit back pressure. (See Table 1.)

Case 2 represents the simplest air compressor control scheme: a fixed displacement air compressor operating at a constant pressure and flow rate. Case 3 represents the second most simple air compressor control scheme: a fixed displacement air compressor operating into a variable pressure. Case 4 represents an air compressor control scheme where the flow rate is varied depending on electrical load but the cathode air pressure is maintained. Case 5 represents the most complicated air compressor control scheme: variable flow rate and air pressure. By only providing the flow rate and pressure necessary to operate the fuel cell stack, the minimum energy is used. It should be noted that for all 4 dynamic cases the effective compressor was turned off during zero power periods of the DST.

Case	Electrical Load	Air Stoichiometry (s)	Cathode Air flow	Cathode Exit Air Temp.	Cathode Exit Back Pressure
1	0 to 2400 W	2	Variable	60 °C	3 Bar
2	DST Load	Variable	116 SLM	60 °C	3 Bar
3	DST Load	Variable	116 SLM	60 °C	2 to 3. Bar
4	DST Load	2*	Varying	60 °C	3 Bar
5	DST Load	2**	Varying	60 °C	1.4 to 3 Bar

*Minimum flow rate was set to 40 SLM to minimize cell water flooding **60 SLM to minimize cell water flooding

RESULTS

Due to the brevity of this abstract the following analysis and results are presented in a reduced form: stack efficiency and net efficiency results only.

Each of the dynamic cases were averaged over three consecutive DST cycles. By integrating the power and current over the three cycles, a total Watt hours and amp hours were found. The fuel cell stack conversion efficiency was then determined utilizing Equation (1). A major consumer of the fuel cell power is the cathode air compressor[6]. To achieve a suitable power density the cathode air is compressed to increase the partial pressure of oxygen and thus increase the fuel cell electrode kinetics. The conducted experiments monitored cathode inlet flow rate and pressure. For this paper the compressor energy required to supply the fuel cell was calculated from the adiabatic compression equation[7]. (See Equation 2.) Adiabatic compression was chosen as a close approximation of real compression (somewhere between adiabatic and isothermal). No allowance was made for pressure recovery at the cathode air exit. Using measured cathode pressure and flow rates the dynamic power requirements for the adiabatic compressor was calculated and integrated over the DST cycles. By subtracting the compressor energy from the fuel cell stack energy the net energy and resultant efficiency were calculated. (See Equation 3.) During zero power periods in the DST the effective compressor was turned off, and hence the energy of compression was zero for those periods.

Stack Efficiency:

$$\frac{\int V(t) \times I(t)\,dt}{\int I(t)\,dt} \times \frac{100\%}{35 \times 1.25}\ (\%) \qquad (1)$$

Compressor:
Power:

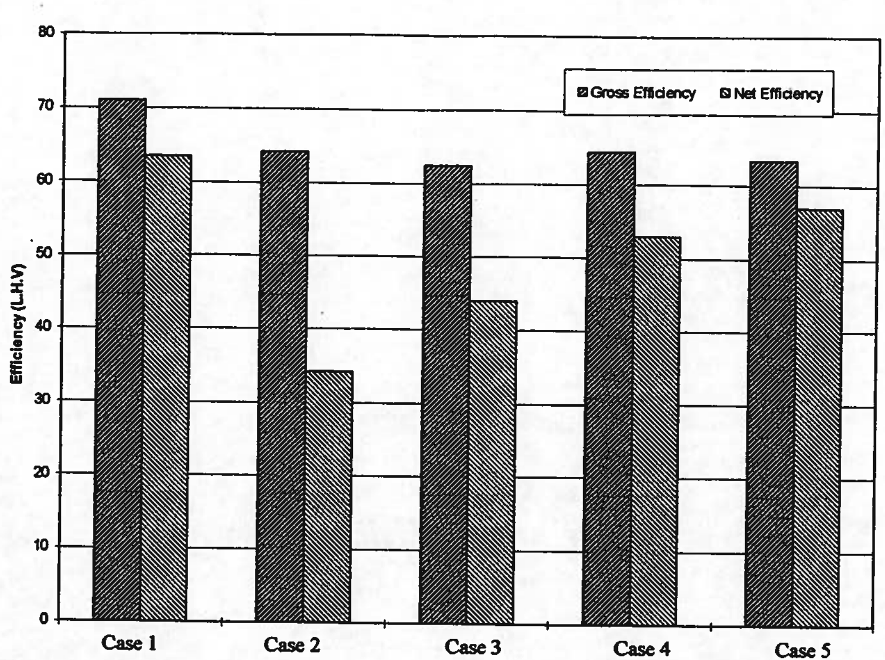
$$P_c = C_p \times T_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} - 1\right] \times SLM \times \frac{1\mathrm{min}}{60\mathrm{sec}} \times \frac{1}{v} \times M\ \text{(Watts)} \qquad (2)$$

Net Efficiency:

$$\frac{\int V(t) \times I(t)\,dt - \int P_c(t)\,dt}{\int I(t)\,dt} \times \frac{100\%}{35 \times 1.25}\ (\%) \qquad (3)$$

Where	C_p	*Specific Heat (Air 1.004 J/(g K),*	V	*Stack Voltage (volts),*
	T_1	*Compressor Inlet Air Temperature (K),*	I	*Stack Current (amps),*
	P_1	*Compressor Inlet Air Pressure (bar),*	k	*Specific Heat Ratio,*
	P_2	*Compressor Outlet Air Pressure (bar),*	*35*	*Cells in the Stack.*
	v	*Specific Volume on a Molar Basis (22.4 L/Mole),*		
	M	*Molecular Mass (28.97 g/mole for Air),*		
	1.25	*Theoretical Cell Voltage Based on Enthalpy of Formation (Lower) (volts),*		

The resultant stack and net efficiencies for the 5 different cases are presented in the following bar chart.



SUMMARY

The varying driving load of an electric vehicle influences the net efficiency of a fuel cell power system. Using the USABC Dynamic Stress Test the operating efficiency of a 35 cell PEM fuel cell stack was measured and compared to its steady state performance at the same average power level. The following bullets summarize the findings;

1) For the same average power the stack efficiency of a dynamic cycle will be less than that at a steady power. This effect is predominately the result of increased IR losses during the high power levels of the DST resulting in a lower integrated cycle efficiency.
2) Compression for the cathode air supply can have a significant impact on fuel cell system net efficiency and power. The air compressor control is critical over a dynamic cycle. By load following in cathode air flow rate and pressure the net efficiency is significantly increased. (Compare Case 2 with Case 5 in Figure 3.)

ACKNOWLEDGMENTS

The authors wish to thank Ballard Power Systems and California Department of Transportation (New Technologies Division) for the support they have. We also wish to thank the University of California Transportation Center for supporting students involved in this project.

REFERENCES

[1] D.H. Swan, B.E. Dickinson, and M.P. Arikara, "Proton Exchange Membrane Fuel Cell Characterization for Electric Vehicle Applications," SAE Paper 940296, presented at the 1994 SAE International Congress, Detroit, Michigan (February 28 - March 3).

[2] Julio C.T. Oliveira, A. Anantaraman and W.A. Adams. "Performance Evaluation of a H_2/Air PEM-FC System under Variable Load." 1992 Fuel Cell Seminar: Fuel Cell Program and Extracts, pp. 451-454 (1992

[3] B.E. Dickinson, T. Lalk, and D. G. Hervey. "Characterization of a Fuel Cell/Battery Hybrid System for Electric Vehicle Applications." SAE Paper 931818. Electric Vehicles Power Systems. Warrendale, Pennsylvania: SAE, Inc., Special Publication 984, pp. 121-129 (August 1993).

[4] P.F. Howard, and C.J. Greenhill. "Ballard PEM Fuel Cell Powered ZEV Bus." SAE Paper 931817. Electric Vehicle Power Systems. Warrendale, Pennsylvania: SAE Inc., Special Publication 984, pp. 113-120 (August 1993).

[5] U.S. Department of Energy. Idaho National Engineering Laboratory. *USABC Electric Vehicle Battery Test Procedures Manual: Revision 1*, Report DOE/ID-10479, July 1994.

[6] D.H. Swan, and A.J. Appleby. "Fuel Cells for Electric Vehicles, Knowledge Gaps and Development Priorities." Proceedings of The Urban Electric Vehicle, Stockholm, Sweden, pp 457-468 (May 1992).

[7] Kenneth Wark. Thermodynamics. New York: McGraw-Hill Book Company, 1983, p. 628.