Fuel Cell Systems Analysis

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Objectives

- Develop a validated model for automotive fuel cell systems and periodically update it to assess the status of technology.
- Conduct studies to improve performance and packaging, to reduce cost, and to identify key R&D issues.
- Compare and assess alternative configurations and systems for transportation and stationary applications.
- Support DOE/FreedomCAR automotive fuel cell (FC) development efforts.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

- A. Compressors/Expanders
- D. Fuel Cell Power System Benchmarking
- F. Heat Utilization
- H. Start-up Time
- I. Fuel Processor Start-up/Transient Operation
- M. Fuel Processor System Integration and Efficiency
- R. Thermal and Water Management

Approach

- Develop, document and make available an efficient and versatile system design and analysis tool.
- Validate the model against data obtained in laboratory and at Argonne's Fuel Cell Test Facility.
- Apply model to issues of current interest.

Accomplishments

- Supported revision of compressor-expander module (CEM) targets by analyzing power consumed by the air management subsystem on standard drive cycles for direct H_2 and gasoline reformed FC vehicles.
- Supported setting of H_2 storage targets by analyzing the fuel economy of FC vehicles.
- Developed dynamic models of compressor, expander and motor on a single shaft; ram-air cooled condenser and radiator; catalytic water gas shift (WGS) and auto-thermal reactor (ATR) on microlith supports; and monolith-supported preferential oxidation (PrOx).
- Proposed and analyzed fuel cell systems for hybrid vehicles.

- Analyzed data for Nuvera system obtained at Argonne's Fuel Cell Test Facility.
- Evaluated FC systems for combined heat and power.

Future Directions

- Perform drive cycle analyses of direct hydrogen and reformed FC systems.
- Analyze FC systems for combined heat and power for stationary applications.
- Support fuel processor engineering projects at Argonne National Laboratory.
- Continue to support DOE/FreedomCAR development efforts.

Introduction

While different developers are addressing improvements in individual components and subsystems in automotive fuel cell propulsion systems (e.g., cells, stacks, fuel processors, balance-of-plant components), we are using modeling and analysis to address issues of thermal and water management; design-point and part-load operation; and component-, system-, and vehicle-level efficiencies and fuel economies. Such analyses are essential for effective system integration.

Approach

Two sets of models are being developed. GCtool is a stand-alone code with capabilities for design, off-design, steady state, transient and constrained optimization analyses of FC systems. GCtool-ENG has an alternate set of models with a built-in procedure for translation to the MATLAB/SIMULINK platform commonly used in vehicle codes such as PSAT (vehicle simulation software package developed at Argonne).

Results

One of the major activities in FY 2003 was to model and analyze pressurized direct hydrogen fuel cell systems for hybrid vehicles. The modeled system, shown in Figure 1, uses compressed hydrogen fuel and operates at 2.5 atm, 80ºC, and a cell potential of 0.7 V at the rated power point. It is humidified to 90% relative humidity at the stack temperature using process water and heat from the stack coolant, as is the cathode air discharged from the compressor. Process water is recovered from spent air in an inertial separator just downstream of the stack, in a condenser and in a demister at the turbine exhaust. The waste heat transferred to the coolant in the stack is either used for humidifying the anode and cathode streams or rejected in a radiator.

Our interest is in a load-following fuel cell system (FCS) coupled to an energy storage device operated in a charge-sustaining mode. For this type of hybrid system, the FCS alone must be capable of meeting the vehicle power demand under all sustained driving conditions. The minimum size of the FCS is then determined by the power demand at the top sustained speed, taken as 100 mph, or the power necessary to maintain the vehicle at 55 mph at 6.5% grade for 20 min. With battery assist, the FCS must have the response time to allow the vehicle to accelerate from 0 to 60 mph (Z-60) in a specified time, taken as 10 seconds. To be competitive with its internal combustion engine counterpart, the FCS must have 1-s transient response time for 10% to 90% power and be able to reach maximum power from cold start in 15 s at 20^{o}C ambient temperature and in 30 s at -20^{o}C ambient temperature. We further require that the FCS be 50% efficient at the rated power and be water balanced for all rated loads at 50% oxidant utilization and ambient temperatures up to 42^{o}C.

Our analyses show that the air management system, i.e., the compressor, expander and motor, must be oversized to meet the cold start-up time targets. To meet the 1-s transient time target, over short time periods, the electric motor has to be overloaded and the maximum oxidant utilization, generally limited to 50%, is allowed to rise to 60%.

FCS for Hybrid Mid-Size SUV. With the requirements and approach defined above, Table

1 lists the attributes of three FCSs for a hybrid mid-size SUV. The minimum rating of the FCS is 80 kW; it is determined by the sustained top speed rather than the gradeability criterion. The minimum power rating for the energy storage system (ESS) is the difference between the maximum power demand at Z-60 and the rating of the FCS. FCS-1 is a 100-kW system without an expander. It needs a rather large 27-kW motor for the air management system. FCS-2 is a 100-kW system with an expander and a motor which is one-third the size of the motor in FCS-1. FCS-3 is a 160-kW system with an expander. It can potentially power the SUV without battery assist. Under all conditions, FCS-3 has the highest efficiency and FCS-1 the lowest efficiency.

Stack Performance. Figure 1 shows the behavior of the stack for FCS-2, the 100-kW system with an expander. Under warm conditions, it produces about 105 kWe at the rated power point. With the air management system oversized to satisfy the cold start-up time requirement, it can generate 120 kWe at a cell voltage of 0.65 V. At 20^{o}C, the power is 20% lower with the cell voltage decreasing to 0.55 V. At -20^{o}C, the stack is derated by 35% and the cell voltage goes down to 0.45 V. With the oversized

Table 1. FCS for Hybrid Mid-Size SUV (AWD = all wheel drive, GVW = gross vehicle weight)

	Mid-Size AWD SUV		
GVW with FCS	2400 kg	Frontal Area	2.46 m^2
Coef. Rolling Fraction	0.0084	Drag Coef.	0.41
	Traction Power Requirement		
Z-60	160 kWe		
Top Speed (100 mph)	80 kWe		
6.5% Grade (55 mph)	70 kWe		
	FCS - 1	FCS - 2	FCS - 3
Rated Power at 0.7 V	100 kWe	100 kWe	160 kWe
Air Management System	w/o Expander	with Expander	with Expander
CEM M/C Power	27.3 kW	9.5 kW	15.1 kW
FCS Efficiency			
@ Rated Power	47%	54%	54%
@ 25% of Rated Power	61%	63%	63%
@ 80 kWe	52%	56%	59%
@ 20 kWe	62%	63%	64%

CEM, the net derating is only 10% at 20^{o}C and 25% at -20^{o}C.

Heat Rejection System. Our analyses show that the size of the heat rejection system for the SUV is determined by the gradeability condition rather than the top sustained speed. Shown in Figure 3 are the heat duties and the heat rejection capabilities as a function of vehicle speed. For FCS-3, the 160-kW system with an expander, the heat duty is zero at speeds less than 60 mph, implying that the stack cannot be maintained at 80^{o}C at low speeds. A radiator sized for heat duty at 6.5% grade at 55 mph can meet the heat rejection requirements at all speeds. Because the maximum heat rejection is greater than the heat duty, a thermostatic control is required.

The trends of heat duty and heat rejection are similar for FCS-2, the 100-kW system with an expander, but with one important difference. The

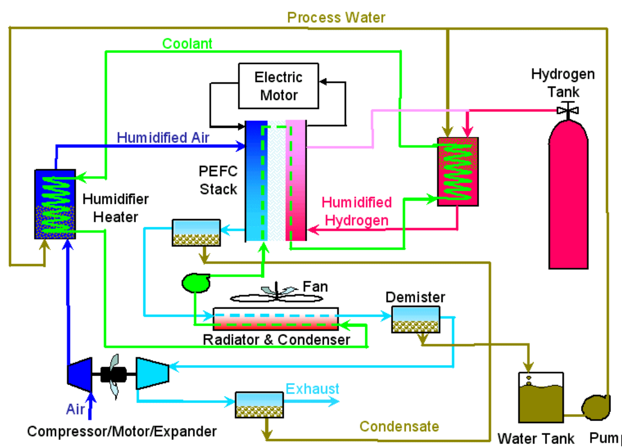

Figure 1. Pressurized Direct H_2 Fuel Cell System

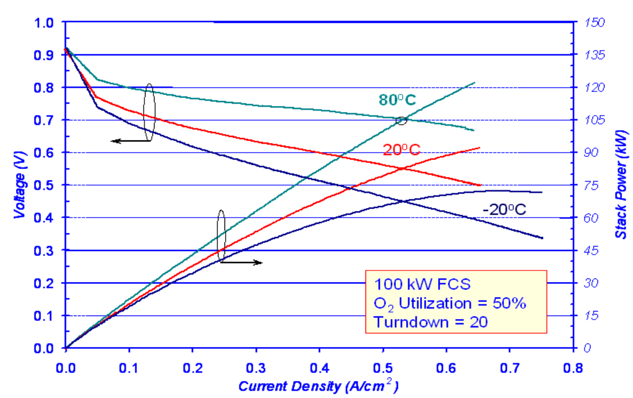

Figure 2. Stack Behavior with Oversized CEM

heat duty at the gradeability condition is nearly twice as large even though the FCS is 60% smaller.

Water Management System. The results in Figure 4 indicate that the criterion for sizing the water management system changes with FCS rating. For FCS-3, the 160-kW system, the maximum heat duty levels off after 80 mph. A condenser sized for heat duty at 6.5% grade at 55 mph can meet heat rejection requirements at all speeds.

For FCS-2, the 100-kW system, the heat duty peaks at about 75 mph. Heat load at grade is no longer the design point, nor is the speed at which the heat load is highest. Instead, the design point is at an intermediate speed of about 70 mph. Unlike the radiator, the condenser for a 100-kW system is smaller than one for a 160-kW system.

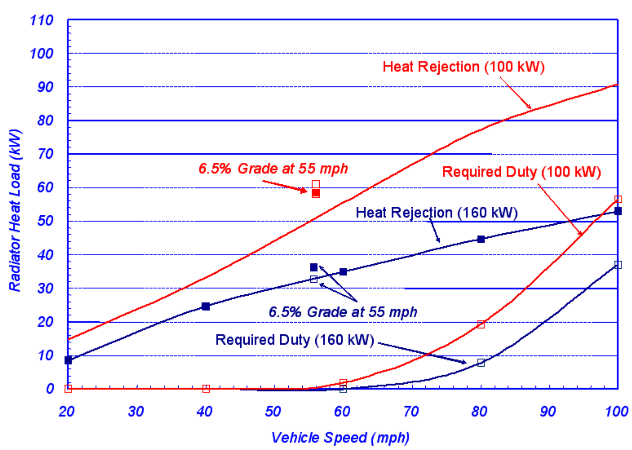

Figure 3. Heat Loads on the Stack Radiator

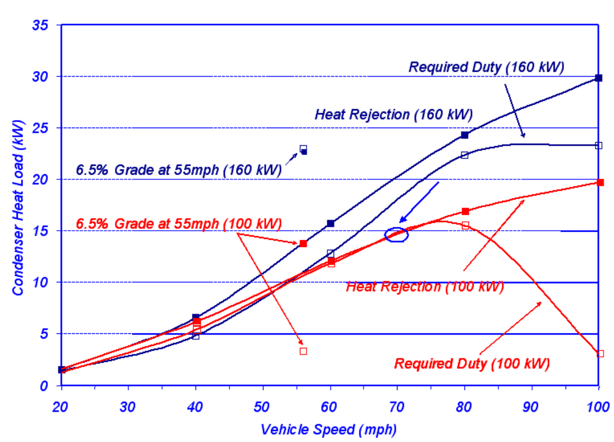

Figure 4. Heat Loads on the Water Recovery Condenser

CEM Idle Speed. Our work on the air management system has looked at the issues of idle speed and maximum turndown. For reference, idle speed is the minimum rpm at which the air management system can provide sufficient cathode air to enable the FCS to generate the power needed by the CEM if it was overloaded to meet a sudden surge in power demand. Idle speed is an important parameter that affects the system efficiency at part load as well as oxygen utilization and water recovery. It is determined by the motor power, the motor/controller algorithm and the physical design of the rotating turbomachinery.

For a high speed, matched, turbo compressor/expander set, we have determined that with an expander, the maximum turndown can be as high as 20. Without an expander in the system, the maximum turndown can be as low as 5.

FCS Efficiency. Figure 5 shows the effect of CEM turndown on FCS efficiency over the Federal Urban Driving cycle (FUDS) for FCS-2, the 100-kW system with an expander. Results are presented for CEM turndowns of 5 and 20. Differences in efficiency are clearly evident at low loads. Both give efficiencies in excess of 60% over FUDS, but with a turndown of 20, the peak efficiency can exceed 70% at low loads. However, the scatter in dynamic efficiency is wider at a maximum turndown of 20.

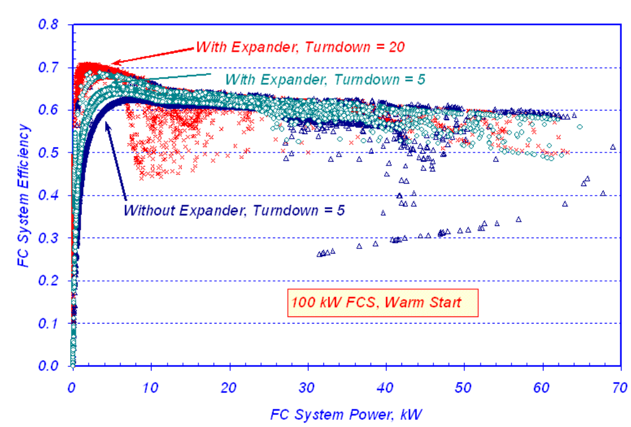

Figure 5. Effects of CEM Turndown and Expander on FCS Efficiency over FUDS

This scatter is largely due to acceleration demand near idling speeds.

Also shown in Figure 5 is the contribution of the expander to FCS efficiency over FUDS. Comparing the results for FCS-2 and FCS-1, the 100-kW systems with and without an expander, differences in efficiency at high loads are due to the additional power generated by the expander and at low loads due to the larger turndown obtainable with an expander in the system. Without an expander, the dynamic fluctuations in efficiency are minor at low loads but can be substantial at high loads.

Oxygen Utilization. Figure 6 shows that in a load-following FCS, oxygen utilization cannot be held constant over driving cycles. This is because of the inertia of the rotating components comprising the air management system and the finite turndown. In particular, oxygen utilization is close to zero during idling conditions and is low during deceleration. The system cannot be water-balanced at low O_2 utilization. In our dynamic simulations, we attempt to maintain the water tank at a constant level by recovering excess water at high loads to compensate for water being consumed at low loads.

Conclusions

- The air management system plays an important role in determining the transient response, cold start-up and part-load performance of a pressurized FCS.

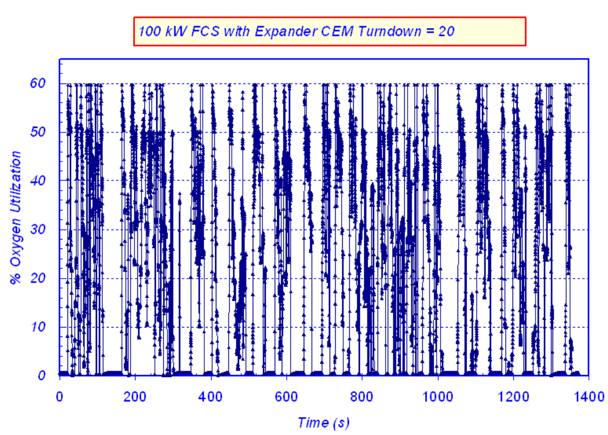

Figure 6. Oxygen Utilization over FUDS

- The size of the heat rejection system for a hybrid mid-size SUV is determined by the gradeability condition rather than the top sustained speed.
- The efficiency at part load and the dynamic fluctuations in efficiency depend on the maximum CEM turndown and the presence of an expander in the system.
- In load-following FCSs, oxygen utilization cannot be held constant over driving cycles. Although it is not possible for the FCS to be water balanced during periods of low oxygen utilization, it can be water neutral over a driving cycle.

FY 2003 Publications/Presentations

1. Ahluwalia, R. K., Deville, B., Rousseau, A., Doss, E. D., Zhang, Q., and Kumar, R., "Performance of Hydrogen Fuel Cell Systems and Vehicles," Third IEA Annex XV Meeting, Düsseldorf, Germany, June 28, 2002.
2. Ahluwalia, R. K. and Milliken, J., "Hydrogen, Fuel Cells and Infrastructure Technologies," World Renewables Energy Congress, Cologne, Germany, July 1-5, 2002.
3. Ahluwalia, R. K., Wang, X., and Rousseau, A., "Direct Hydrogen Fuel Cell Systems for Transportation," Fourth IEA Annex XV Meeting, Palm Springs, CA, November 17-18, 2002.
4. Ahluwalia, R. K., Wang, X., and Rousseau, A., "Direct Hydrogen Fuel Cell Systems for Hybrid Vehicles," Fifth IEA Annex XV Meeting, Stockholm, Sweden, June 17-18, 2003.
5. Ahluwalia, R. K., Doss, E. D., and Kumar, R., "Performance of High-Temperature Polymer Electrolyte Fuel Cell Systems," Journal of Power Sources, 117, 45-60, 2003.