IV.H Transportation Systems and Balance of Plant Components

IV.H.1 Fuel Cell Systems Analysis

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Objectives

- Develop and validate a 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 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 Research, Development and Demonstration Plan:

- A. Compressors/Expanders
- C. Fuel Cell Power System Benchmarking
- D. Heat Utilization
- H. Start-up Time
- 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 models against data obtained in laboratories and at Argonne's Fuel Cell Test Facility.
- Apply models to issues of current interest.

Accomplishments

- Analyzed data taken at Argonne's Fuel Cell Test Facility.
- Established efficiency targets for membrane-based fuel processors.
- Evaluated thermal and water management requirements and subsystem.
- Assessed the effect of humidity on high-temperature membrane fuel cell (FC) system.
- Evaluated performance of polymer electrolyte fuel cell (PEFC) systems for combined heat and power.
- Analyzed fuel cell systems for hybrid vehicles.

Future Directions

- Perform drive cycle analyses of ambient-pressure hydrogen FC systems.
- Initiate study on cold start of hydrogen FC systems.
- Support fuel processor engineering projects at Argonne National Laboratory (ANL).
- 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 (software package developed at ANL for analysis of FCs and other power systems) 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 (a vehicle simulation software package developed at ANL).

Results

We analyzed the problems of thermal and water management in a pressurized fuel cell system (FCS) with a condenser for water recovery and two coolant circuits (see Figure 1). The stack waste heat transferred to the coolant in the high-temperature circuit is either rejected in a radiator at 70-80°C or used to condition and humidify the anode and cathode streams. The coolant in the low-temperature circuit leaves the radiator at less than 55°C and functions as the heat sink for the water recovery condenser, the traction inverter motor (TIM) and optionally the condenser of the vehicle's air-conditioning system. Figure 2 shows the simulated heat duties on the radiators, air pre-heater, TIM, and the water-recovery condenser for a 120-kW$_e$ FC system for a mid-size family sedan as functions of vehicle speed and on a 6.5% grade at 55 mph. Our analyses indicate that the FCS needs bulky radiators, a 700-W blower fan and an air pre-heater of 20 kW heat duty. With this configuration, aerodynamic drag induced by the cooling system is a concern, and it is not possible to maintain the stack at the design-point temperature (80°C) at low loads.

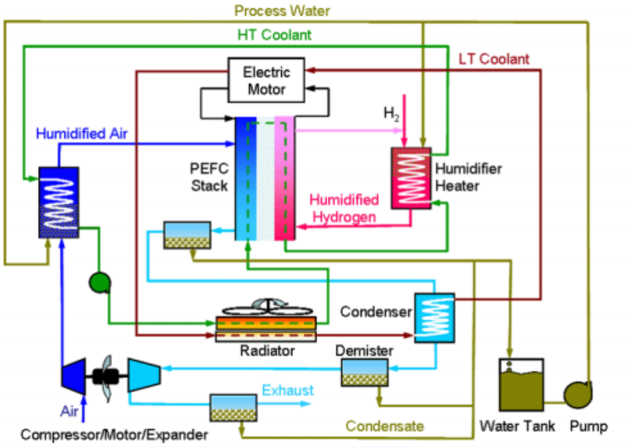

Figure 1. Pressurized FCS with Condenser and Two Coolant Circuits

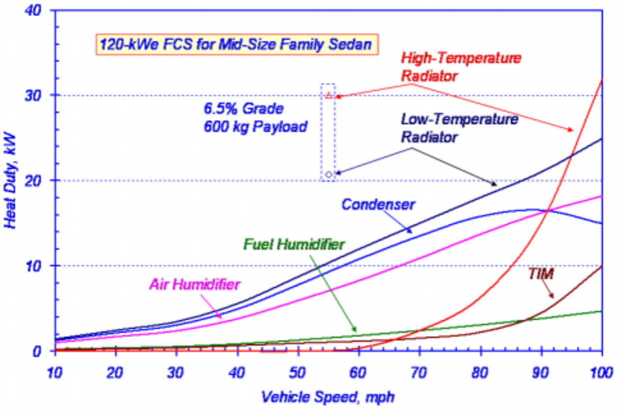

Figure 2. Heat Duties on FCS Components

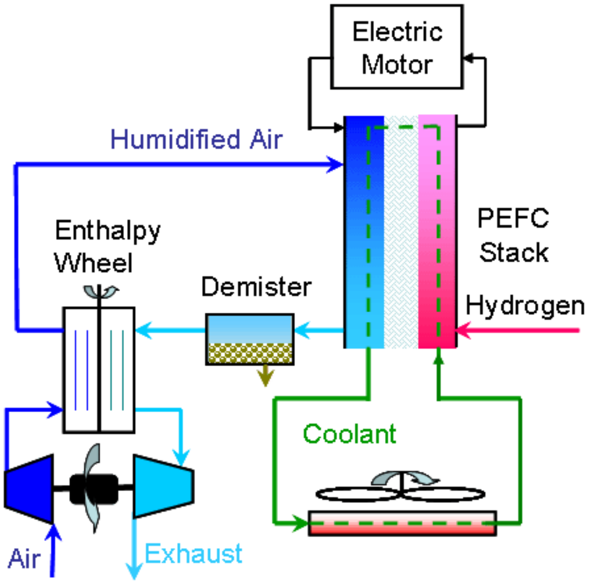

Figure 3. Pressurized FCS with Enthalpy Wheel Humidifier

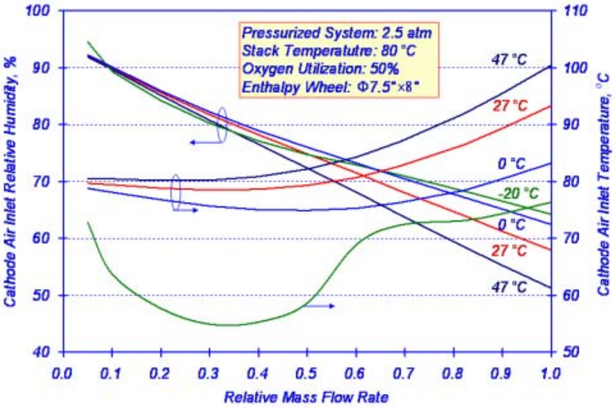

Figure 4. Performance of Enthalpy Wheel Humidifier

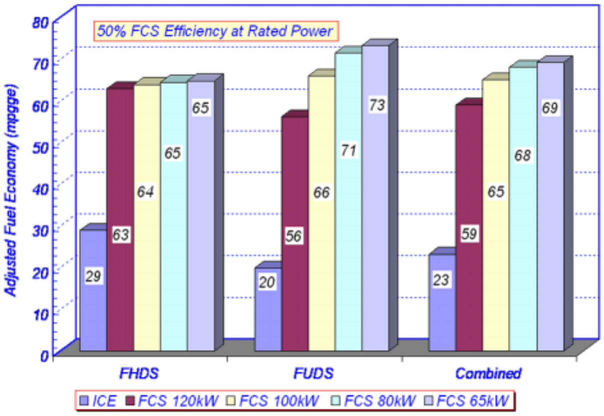

Figure 5. Fuel Economy of Hybrid FC Vehicles over FHDS and FUDS

Figure 3 displays an alternate thermal and water management subsystem in which an enthalpy wheel humidifies the cathode stream by transferring moisture from the spent cathode gas. In order to analyze this system, we developed a transient multi-nodal model for an enthalpy wheel and validated it against experimental data obtained at different wheel speeds, flow rates, stack temperatures and pressures. Figure 4 shows that a 7.5" (diameter) x 8" (long) enthalpy wheel rotating at 40 rpm can humidify the cathode air for a 120-kW$_e$ FCS to 50-65% relative humidity (RH) at 2.5 atm using spent cathode air from a stack at 80°C with 50% oxygen utilization. The level of humidification achieved increases to 90% RH as the flow rate is decreased to 10% and the pressure to 1.1 atm. With this configuration, the stack can be maintained at the design-point temperature at all loads.

In FY 2004, we conducted a study on the fuel economy of hybrid vehicles powered with load-following fuel cell systems and lithium-ion battery energy storage systems (ESSs) operated in a charge-sustaining mode. Figure 5 compares the computed fuel economies of three FC hybrid vehicles with that of a conventional internal combustion engine (ICE) vehicle on the same platform. Of the four FC vehicles considered, one is powered with a stand-alone 120-kW$_e$ FCS and another with the smallest FCS (and 55-kW$_e$ ESS) that can meet the 65-kW$_e$ sustained power requirement for 100-mph top speed. Our simulations indicate that over the combined Federal Highway (FHDS) and Urban (FUDS) Driving Schedules, the stand-alone FC vehicle can achieve 2.5 times the fuel economy of the ICE vehicle. The fuel economy multiplier can be raised to 3 by hybridizing the FCS with an ESS. Some other important conclusions from our study are summarized below.

- The improvement in fuel economy of FC vehicles with hybridization depends on the drive cycles. Compared to a stand-alone FC vehicle, there is a potential for 30-34% improvement on FUDS and the Japanese J1015 cycle in which, without regenerative braking, >50% of the traction energy would be dissipated in mechanical braking. On FHDS, the potential improvement in fuel economy with hybridization is only 3%.

- The fraction of the braking energy that is recovered by the ESS and is available for traction depends on the drive cycle and the size of the ESS. On FUDS, 56% of the braking energy is recoverable with a 20-kW$_e$ ESS, 86% with a 40-kW$_e$ ESS and 95% with a 55-kW$_e$ ESS.
- The improvement in fuel economy also depends on the degree of hybridization. Whereas the fractional recovery of braking energy increases as the ESS is made larger, the cumulative efficiency of the FCS over the drive cycle decreases as the FCS is made smaller.
- FCS efficiency at rated power has only a small influence on the overall fuel economy. There is less than 2 mpgge (miles per gallon gasoline equivalent) difference in fuel economy of a vehicle with a 50%-efficient FCS (680 mV cell voltage at rated power) and a vehicle with a 40%-efficient FCS (560 mV cell voltage at rated power).

In FY 2004, we also did a study on the performance of reformed natural gas (NG) fuel cell systems for residential combined heat and power and addressed the problem of mismatch between thermal and electric demands that results in underutilization of the FCS and the available thermal energy. For a typical 1200-ft^2 single-family residence in Chicago, we compared a baseline system that uses a 5.5-kW$_e$ FCS and a NG furnace for supplemental space heating with an alternative system that uses the FCS and a heat pump. Some important conclusions are highlighted below (see Figure 6).

- In the baseline system, the FCS utilization is low, the peak power is <1.6 kW$_e$, and the peak FCS thermal efficiency is 46.9%. In the alternative system, the FCS utilization is high, the peak power is 5.2 kW$_e$, and the peak FCS thermal efficiency is 53.3%.
- In the baseline system, the waste heat from the FCS is insufficient even to meet the domestic hot water (DHW) demand. In the alternative system, the waste heat is used for DHW plus 37% of space heating.

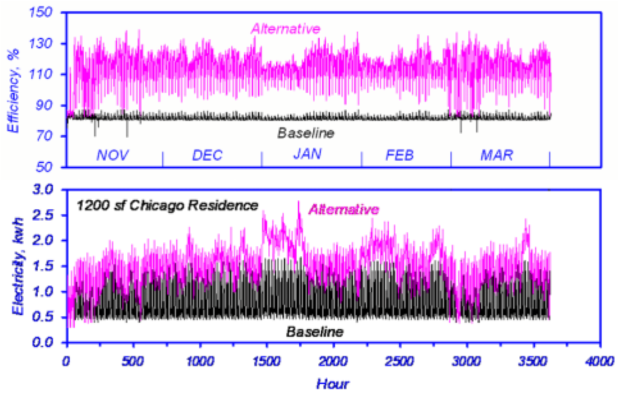

Figure 6. Comparison of FC Systems for Residential Combined Heat and Power

- In the baseline system, the NG furnace provides nearly 100% of the space heating. In the alternative system, 63% of the space heating comes from the FCS-powered heat pump, and the overall energy efficiency is ~115% (compared to 80-90% with NG furnace), resulting in 30% fuel saving in the winter months.

Conclusions

- Radiator size, aerodynamic drag due to the cooling system, and inability to maintain the stack at the design-point temperature at low loads are of concern in FC systems that rely on phase-change devices for humidification and water recovery.
- A 7.5" (diameter) x 8" (long) enthalpy wheel can be designed to humidify the cathode air for a 120-kW$_e$ FCS to 50-65% RH at 2.5 atm and 80°C.
- Hydrogen-fueled FC vehicles can obtain 2.5 times the fuel economy of the conventional ICE vehicles on the same platform. The fuel economy multiplier can be further increased to 3.0 by hybridizing the FCS with an ESS. The actual increase in fuel economy depends on the drive cycle and the degree of hybridization.
- The problem of mismatch between the thermal and electric demands on residential fuel cell systems can be resolved by using a heat pump for space heating in winter months.

FY 2004 Publications/Presentations

1. Doss, E. D., Ahluwalia, R. K., and Wang, X., "PEFC Systems for Building Cooling, Heating, and Power (BCHP)," IEA Annex XI Phase II Meeting, Trondhein, Norway, May 6-7, 2003.

2. 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.

3. Doss, E. D., Ahluwalia, R. K., and Kumar, R., "Thermal Integration and Water Management Systems for Fuel Cells," 204th Meeting of the Electrochemical Society, Orlando, FL, October 12-17, 2003.

4. Kumar, R. and Ahluwalia, R. K., "Hydrogen Fuel Cell Vehicles – The Potential for Fuel Economy Gains Over Conventional Petrol Vehicles," Business Briefing: Global Automotive Manufacturing & Technology, pp. 1-5, 2003.

5. Hua, T. Q., Ahluwalia, R. K., Wang, X., and Myers, D. J., "Fuel Cell System and Heat Pump for Residential Combined Heat and Power," IEA Annex XI Phase II Meeting, Miami Beach, FL, November 7-8, 2003.

6. Wang, X., Ahluwalia, R. K., and Myers, D. J., "Direct H_2 Fuel Cell System with High-Temperature Polymer Membrane," IEA Annex XVI Meeting, Newcastle, United Kingdom, May 6-7, 2004.

7. Ahluwalia, R. K., Wang, X., Rousseau, A., and Kumar, R., "Fuel Economy of Hydrogen Fuel Cell Vehicles," Journal of Power Sources, 130, 192-201, 2004.