**Final Abstract**
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# ANALYTICAL PERFORMANCE OF DIRECT-HYDROGEN–FUELED POLYMER ELECTROLYTE FUEL CELL (PEFC) SYSTEMS FOR TRANSPORTATION APPLICATIONS

Ezzat Danial Doss
(630) 252-5967
doss@anl.gov

Rajesh Ahluwalia
(630) 252-5979
walia@td.anl.gov

Romesh Kumar
(630) 252-4342
kumar@cmt.anl.gov

Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

The performance of a stand-alone polymer electrolyte fuel cell (PEFC) system directly fueled by hydrogen has been evaluated for transportation vehicles. The study was carried out using a systems analysis code and a vehicle analysis code. The systems code includes models for the various PEFC components and is applicable for steady-state and transient situations.

At the design point, the system efficiency is above 50% for a 50-kW system. The efficiency improves under partial load and approaches 60% at 40% load, as the fuel cell operating point moves to lower current densities on the V-I polarization curve. At much lower loads, the system efficiency drops because of the deterioration in the performance of the compressor, expander, and eventually the fuel cell. The system performance suffers at lower temperatures, as the V-I characteristic curve for the fuel cell shifts downward because of the increased ohmic losses.

The results of the transient analysis indicate that the hydrogen-fueled PEFC system can start rather rapidly, within seconds from ambient conditions. However, the warm-up time constant to reach the design operating temperatures is about 180 s. It is important during this period for the coolant to bypass the system radiator until the coolant temperature approaches the design temperature for the fuel cell.

The systems analysis code has been applied to two mid-size vehicles: the near-term Ford AIV Sable and the future P2000 vehicle. The results of this study show that the PEFC system in these vehicles can respond well to the demands of the FUDS and Highway driving cycles, with both warm and cold starting conditions. The results also show that the fuel-cell AIV Sable vehicle has impressive gains in fuel economy over that of the internal combustion engine vehicle. However, this vehicle will not be able to meet the PNGV goal of 80 mpg. On the other hand, the P2000 vehicle approaches this goal with variable efficiency of the compressor and expander. It is expected to exceed that goal by a big margin, if the efficiency of the compressor and expander can be maintained constant (at 0.8) over the power range of the fuel cell system.

Acknowledgement: This work was supported by the U. S. Department of Energy, Office of Advanced Automotive Technologies.

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## ABSTRACT

The performance of a stand-alone polymer electrolyte fuel cell (PEFC) system directly fueled by hydrogen has been evaluated for transportation vehicles. The study was carried out using a systems analysis code and a vehicle analysis code. The systems code includes models for the various PEFC components and is applicable for steady-state and transient situations. At the design point, the system efficiency is above 50% for a 50-kW system. The efficiency improves under partial load and approaches 60% at 40% load, as the fuel cell operating point moves to lower current densities on the V-I polarization curve. At much lower loads, the system efficiency drops because of the deterioration in the performance of the compressor, expander, and eventually the fuel cell. The results of the transient analysis indicate that the PEFC system can start rapidly from ambient temperatures (300 K).

The PEFC system has been evaluated for near-term and future mid-size vehicles. The results of the study show that the PEFC system can meet the demands of the Federal Urban Driving Schedule (FUDS) and the Highway driving cycles, for both warm and cold start-up conditions. The results also indicate that the future PEFC vehicle can meet the fuel economy goal of 80 miles per gallon (mpg) equivalent.

## I. INTRODUCTION

Over the past few years, fuel cells, especially the polymer electrolyte fuel cell (PEFC), have shown the promise of becoming a viable option to today's internal combustion engines for transportation applications. The fuel cell can be powered by hydrogen directly or by a hydrogen-rich gas stream produced by reforming hydrocarbon fuels such as natural gas, methanol, or gasoline. This paper is limited to the study of the performance of direct-hydrogen-fueled PEFC systems. Work is in progress to investigate the performance of other fuel cell systems and will be the subject of future papers.

## II. SYSTEMS SIMULATION AND MODELING

Computer modeling of the fuel cell system components and the overall system performance is an ongoing activity at Argonne National Laboratory (ANL). The system configuration is defined in terms of component flows and model task loops, and the component model functions are called in the order that the flows are processed. The system code is capable of handling recycle flows and of performing optimization studies that take into account physical constraints. Iterative tasks are used, as needed, to handle parametric sweeps, system constraints, optimizations, and dynamic time integration. In performing the system simulations, thermodynamic data and physical property calculation utilities for chemical kinetics and multiphase equilibria are used. The thermodynamic property routines available include the water-steam property code, the Lee-Kesler single-species equation of state, the gas-phase chemical equilibrium code (minimization of Gibbs free energy subject to atom balance constraints), and the multiphase chemical equilibrium code. Details of the system code can be found in Reference (1), and the dynamic flow system simulation is described in Reference (2).

The performance of the hydrogen-fueled PEFC system has been examined at steady-state operating conditions under the design and partial loads. The transient behavior of the system was also analyzed to investigate the performance of the fuel cell system for cold- and warm-start conditions. Furthermore, two mid-size vehicles, operating with such a system, were simulated over two driving cycles: the Federal Urban Driving Schedule (FUDS) cycle and the Highway cycle.

## III. STEADY-STATE ANALYSIS

A parametric study has been performed to study the performance of a 50-kW (net power) hydrogen-fueled PEFC system at the design point and partial-load conditions. Figure 1 is a schematic of the 50-kW system. It consists of a fuel reservoir supplying hydrogen at 3 atm to the anode side of the PEFC. A two-stage intercooled compressor supplies the oxidizer air to the cathode side of the PEFC. Downstream of the PEFC, a gas turbine is used to recover the pressure energy in the spent gas. A water tank, pump, and air-cooled radiator comprise the coolant circuit. The pressure, temperature, and mass flow rate for various streams at selected points are shown in Figure 1. For the fuel cell stack, the voltage-current characteristic (polarization curve) is expressed as a function of pressure, temperature, and the fuel and oxidant stoichiometries. The experimental results given in References (3) and (4) are curve fitted and used in the analysis. The input data include results for cell temperatures as low as 293 K (20°C). The average cell current density was taken to be 0.7 A/cm$^2$ at the design point. The fuel-cell active area and the heat-exchanger surface area were calculated and kept constant for simulations in the off-design mode.

For partial-load operations, the compressor, expander, and the fan efficiencies were treated as a function of the mass flow rates through the unit, relative to their design values. The coolant-water flow rate and the air flow rate through the compressor inter-cooler were kept constant, while the air flow rate through the radiator was varied to achieve steady-state conditions for the heat exchanger and the fuel cell. The fuel utilization was kept constant at 100% for all conditions.

Table I presents the results of the study for steady-state operating conditions at 100%, 80%, 60%, 40%, 20%, 15%, 10%, and 0% of the design power level. The fuel and air consumption decrease disproportionately at partial load, and the system becomes more efficient as the stack voltage increases. The coolant temperature (not shown in the Table I) gradually increases from 323 K (50°C) at the design point to about 353 K (80°C) near zero load, thus approaching the fuel cell temperature.

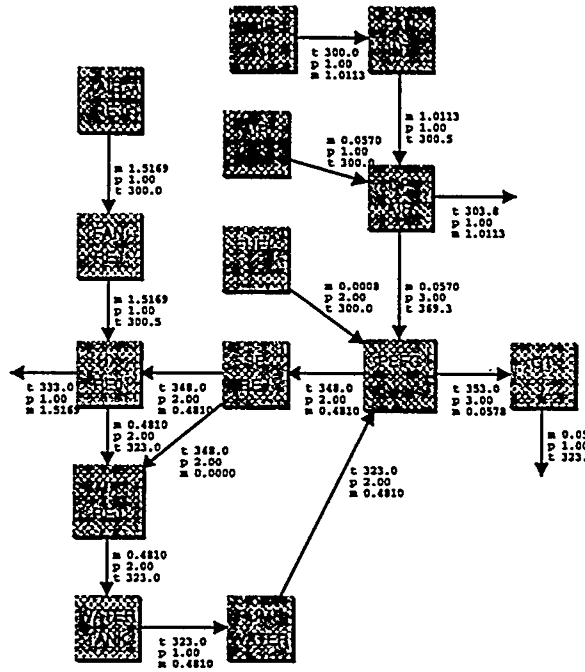

Fig. 1 50-kW Hydrogen-Fueled PEFC System

Another parametric study was performed for the PEFC system start-up from ambient conditions (T = 300 K). In this study, the design parameters for the heat-exchanger surface area and the fuel-cell area were kept constant for partial-load conditions, and the fuel utilization was also kept constant at 100%. However, for this case of cold startup, no air or coolant flow was allowed to pass through the radiator, as the coolant flow bypasses the radiator. The results indicate that the fuel cell system cannot deliver 50 kW at start-up. The predicted maximum power that can be produced is 38 kW, with a corresponding efficiency of 36.3%. The reason for that is the low starting temperature of the fuel cell, which affects the cell voltage-current (V-I) characteristics (polarization curve).

The results show also that sufficient water is formed from electrochemical oxidization of hydrogen at 100% fuel utilization and 3 atm pressure; thus, a humidifier is not required to maintain the PEFC membrane wet.

*Table 1. Results for 50-kW Hydrogen-Fueled Polymer Electrolyte Fuel Cell System*

| Net Power (kW) | Gross Power (kW) | Stack Volts (V) | Stack Amps (A) | System Efficiency (%) | Fuel Flow (g/s) | Air Flow (g/s) | Exhaust Flow (g/s) | Pump/ Fan Power (kW) | Compressor Power (kW) | Expander Power (kW) | Radiator Duty (kW) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 53.89 | 100.0 | 538.5 | 50.8 | 0.821 | 57.0 | 57.83 | 1.443 | 7.44 | 4.99 | 50.29 |
| 40 | 42.79 | 110.0 | 389.1 | 56.2 | 0.594 | 41.2 | 41.79 | 1.020 | 5.37 | 3.60 | 32.50 |
| 30 | 32.50 | 117.2 | 277.3 | 59.1 | 0.423 | 29.4 | 29.78 | 0.942 | 4.01 | 2.45 | 21.25 |
| 20 | 22.66 | 123.5 | 183.5 | 59.6 | 0.280 | 19.4 | 19.70 | 0.880 | 3.15 | 1.37 | 13.16 |
| 10 | 12.72 | 130.0 | 97.9 | 55.9 | 0.149 | 10.4 | 10.51 | 0.811 | 2.42 | 0.51 | 6.77 |
| 7.5 | 10.14 | 131.8 | 76.9 | 53.3 | 0.117 | 8.2 | 8.26 | 0.787 | 2.21 | 0.34 | 5.34 |
| 5 | 7.45 | 134.0 | 55.6 | 49.2 | 0.085 | 5.9 | 5.97 | 0.757 | 1.90 | 0.21 | 3.90 |
| 0 | 1.09 | 143.3 | 7.6 | 0 | 0.012 | 0.8 | 0.82 | 0.647 | 0.46 | 0.02 | 0.59 |

## IV. TRANSIENT ANALYSIS

An analysis was carried out to examine the performance of the 50-kW hydrogen-fueled PEFC system as it was started up from the ambient condition (300 K). The temperature and the mass of the coolant inside the water tank were allowed to vary with time, as the temperature of the coolant flowing into the tank could be different from that inside the tank. The fuel cell is treated as a control volume with specified values for the weight, surface area, heat transfer coefficient, and specific heat. The dynamic models used in the analysis are described in detail in Reference (2).

The start-up procedure of the system was carried out over ramp-up times of 10, 5, and 1 s. During the start-up, the flow rates of the fuel ($H_2$), compressor air, fan air, and cooling water were increased linearly to their steady-state values. The computations were carried out for 800 s.

Figure 2 shows the time variation (for the 10-s start-up time) of the fuel cell temperature, the coolant temperature at the exit of the fuel cell, and the tank water temperature. The results indicate a smooth rise in the temperatures, with time, of the fuel cell and cooling water out of the cell. The tank water temperature, however, remained relatively close to the ambient temperature for about 50 s before starting to increase smoothly. In general, the results show that it takes about 600 s for the fuel cell stack to reach its normal operating temperature of 353 K (80°C).

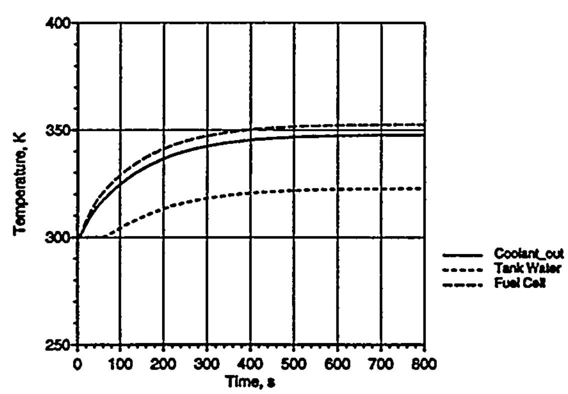


Fig. 2 Start-up of 50-kW Hydrogen PEFC System Fuel Cell and Tank Water Temperatures

Figure 3 presents the time variation of the cell voltage and current density. The variation during the ramp-up time of 10 s is due mainly to starting from near open-circuit conditions, with high voltage and very little or no current. Once the design mass flow rate is reached, the cell current density achieves its steady-state value, while the voltage gradually increases with time toward its design value, as the cell temperature increases.

Figure 4 shows the variation of the system net power with time. The fuel cell responded almost instantly to the increase in the fuel and air flow rates during the 10-s ramp-up of the flow. The system produced about 42 kW (84% of the steady-state value) at the end of the ramp-up time. The power then increased slowly with time over the next several minutes toward its design value of 50 kW. The relatively long time needed for the system to warm up is due to allowing the coolant to pass through the radiator to be cooled, even though the system components are far below their normal operating temperatures.

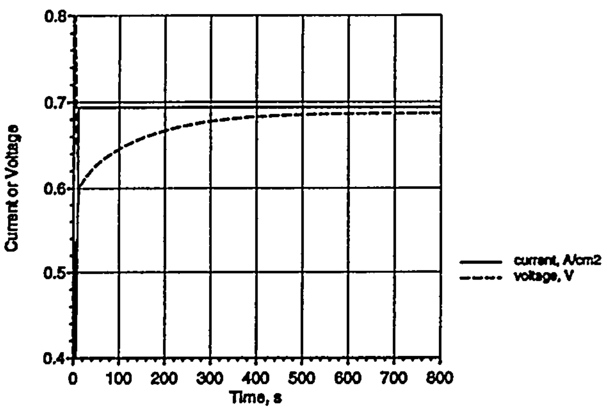


Fig. 3 Start-up of 50-kW Hydrogen PEFC System
Fuel Cell Current Density and Voltage

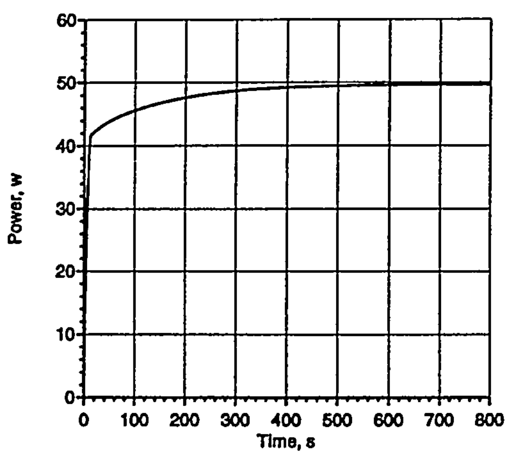


Fig. 4 Start-up of 50-kW Hydrogen PEFC System
Fuel Cell Net Power

Another study was performed that yielded a quicker warm-up of the system. As in the case of conventional vehicles, the PEFC system configuration was modified, as shown in Fig. 1, so that the coolant bypassed the radiator until its temperature reached 348 K (75° C). In this case, the warm-up time for the system was reduced to 180 s. At this point, the fuel cell temperature reached its design value, and the coolant was allowed to flow through the radiator to be cooled down. This process was repeated, leading to the seesaw variation in the coolant temperature inside the water tank, as shown in Fig. 5.

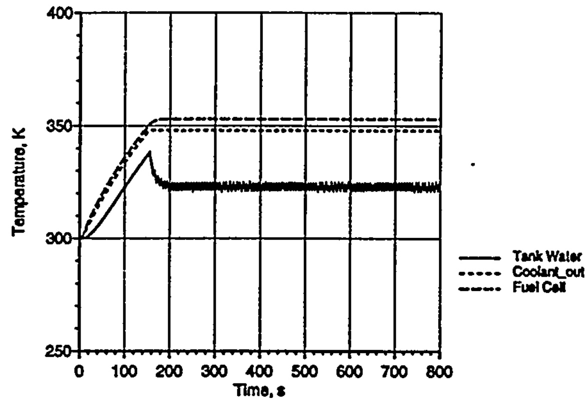


Fig. 5 Start-up of 50-kW Hydrogen PEFC System
with Coolant Bypass
Fuel Cell and Tank Water Temperature

Similar results, as those shown in Fig. 5, were obtained for ramp-up times of 5 and 1 s. The results of this study indicate, in general, that the fuel cell and the system responded almost immediately to the increase of the flow rates, as the fuel cell produced more than 80% of its design power by the end of the ramp-up time.

## V. APPLICATION TO VEHICLE DRIVING CYCLES

Two mid-size vehicles powered by fuel cells were simulated over the Federal Urban Driving Schedule (FUDS) cycle and the Highway cycle. The input data used in the analysis for the two vehicles are for the near-term Ford AIV (Aluminum Intensive Vehicle) Sable and the P2000 future vehicle. The simulation parameters for the two vehicles are given in References 5 and 6 and are shown in Table II.

The variations of the input speeds over the FUDS and Highway driving cycles are presented in Fig. 6. The total distance covered over the FUDS cycle is 7.45 miles over 1371 s, while the corresponding value for the Highway driving cycle is 16.51 miles over 765 s.

Figures 7 and 8 show the instantaneous and the average (from the beginning of the cycle) power requirement for the Ford AIV Sable driven on the FUDS and Highway cycles, as computed from the vehicle analysis code. The maximum power requirement is less than 40 kW for all cases considered, while the maximum average power is only about 8 kW for the FUDS cycle and about 12 kW for the Highway cycle. The computed power requirements for the P2000 vehicle are smaller, as this vehicle has less weight, lower drag resistance, and lower auxiliary load.

*Table II Simulation Parameters for the AIV Sable and P2000 Vehicles*

| Parameter | AIV Sable | P2000 |
|---|---|---|
| Test weight, kg | 1490 | 1043 |
| Frontal area, $m^2$ | 1.98 | 2.18 |
| Drag coefficient | 0.33 | 0.25 |
| Rolling resistance | 0.00776 | 0.0064 |
| Wheel radius, mm | 326 | 326 |
| Auxiliary load, kW | 1.0 | 0.5 |

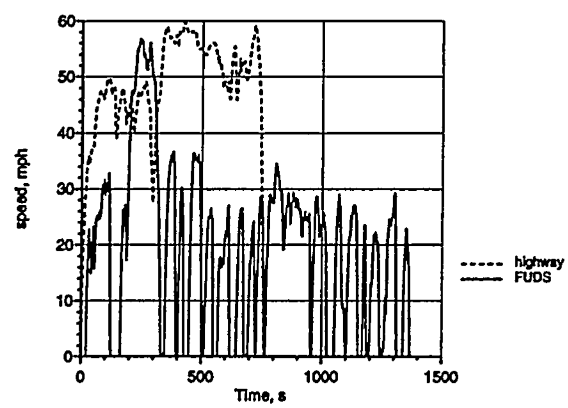

Fig. 6 FUDS and Highway Cycles -- Vehicle Speed

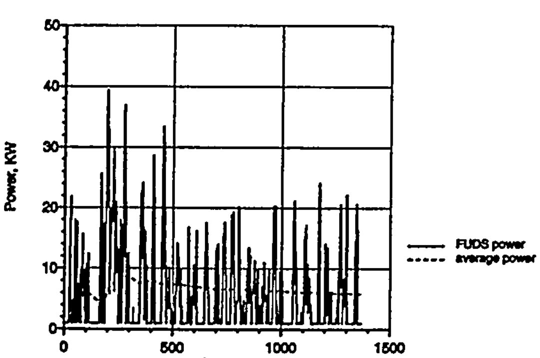

Fig. 7 FUDS and Average Power Required

Another computation was performed to determine the power required for accelerating the vehicle from 0 to 60 mph in 12 s, as specified by the car manufacturers. The results indicate that an 80-kW (net) system is required to meet this performance. Therefore, another simulation was performed with an 80-kW system. This system was used to study the performance of the two mid-size vehicles over the two driving cycles.

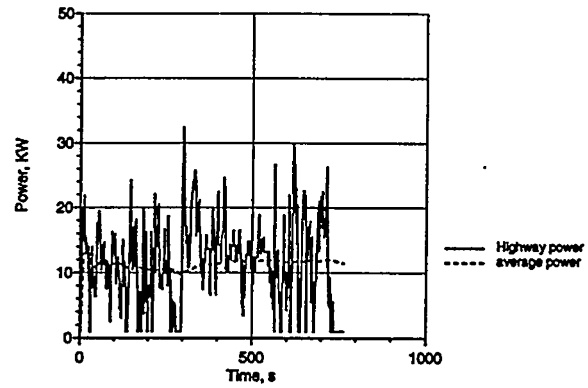

Fig. 8 Highway Cycle and Average Power Required

The following cases were investigated for the two vehicles:

- Starting the FUDS and Highway cycles from the system's design point, where the cell temperature is 353 K (80°C) and the ambient temperature is 300 K (27°C).
- Starting the FUDS and Highway cycles cold, where all system components are at the ambient temperature of 300 K.

These eight cases were analyzed under the assumption that the fans, expander, and compressor efficiencies were kept constant at 0.8. The results obtained can be viewed as showing the upper limit for the performance of the vehicles. The analyses were repeated (eight more cases), except that it was assumed that the efficiencies vary with the flow rate ratio relative to the design value by a factor of 1.0 for 0.6 ratio and above, 0.9 at 0.4 ratio, 0.6 at 0.2 ratio, and 0.3 at 0.1 ratio. Figures 9 and 10 give the results for one of the 16 cases considered: the AIV Sable vehicle over the Highway cycle, starting from the design point (80°C cell temperature). Similar results were obtained for the other 15 cases.

Figure 9 shows the time variation of the fuel-cell system efficiency, its average value, and the overall vehicle efficiency. The calculated PEFC system efficiency is between 66% and 70% most of the time, with an average value approaching 68% near the end of the Highway cycle. The overall vehicle efficiency is lower than the system efficiency, as the auxiliary power (1.0 kW) is subtracted from the fuel cell system power to yield the vehicle traction power requirement. Wherever the fuel cell power requirement is equal to the auxiliary power, the vehicle drive power and overall efficiency become zero. Figure 10 shows the time variation of the fuel (hydrogen) mass flow rate and the cumulative fuel consumption over the Highway cycle. The fuel demand curve follows exactly the highway power requirement presented in Fig. 8.

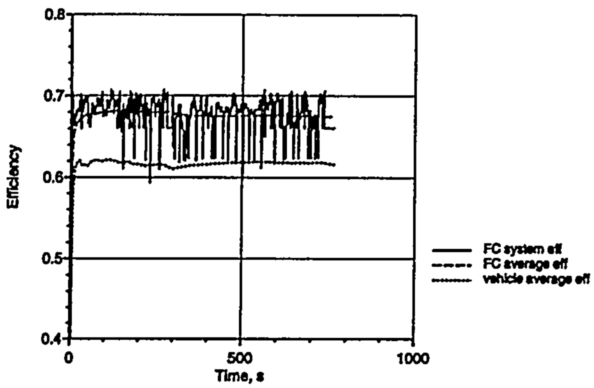


Fig. 9 Fuel Cell System and Vehicle Efficiencies For AIV Sable under Highway Cycle

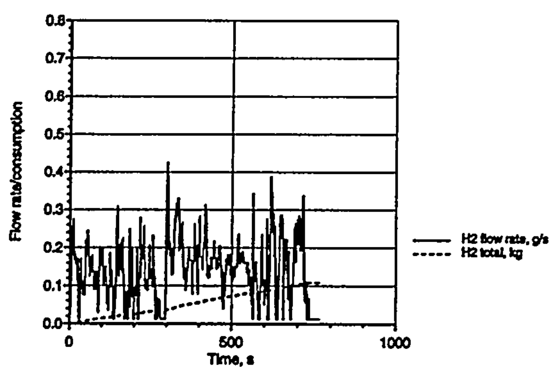


Fig. 10 Hydrogen Consumption for AIV Sable under Highway Cycle

The results for fuel economy in equivalent miles per gallon of gasoline are shown in Fig. 11 for the FUDS, the Highway, and the combined driving cycles. The combined fuel economy on the two driving cycles is calculated as the harmonic average of the two cycles, as follows:

$$(1/\text{combined}) = 0.5\ (1/\text{FUDS} + 1/\text{Highway})$$

The results in Fig. 11 illustate the impact of the compressor and expander efficiencies on the vehicle performance. As these efficiencies drop with decreasing flow rates, the vehicle's system efficiencies drop significantly, and so does the fuel economy.

In general, the results indicate that the fuel cell-powered AIV Sable would show impressive gains in fuel economy over that of the internal combustion engine vehicle. However, it is not able to meet the Partnership for a New Generation of Vehicles (PNGV) goal of 80 mpg. On the other hand, the P2000 vehicle approaches this goal with variable compressor and expander efficiencies. It is expected even to exceed that goal, if the efficiency of the compressor and the expander can be maintained constant (0.8) over the operating power range.

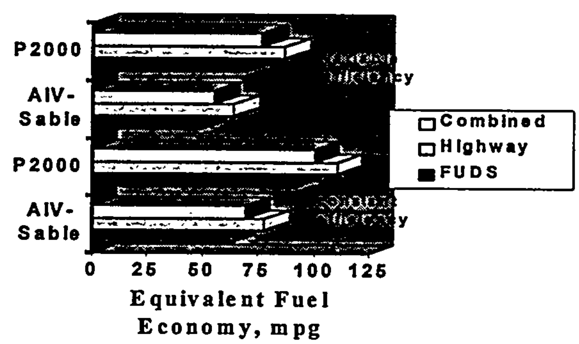


Fig. 11 Fuel Economy of the AIV Sable and the P2000 Vehicles over the FUDS, Highway, and Combined Driving Cycles.

## VI. SUMMARY AND CONCLUSIONS

1. The performance of a stand-alone direct-hydrogen-fueled PEFC system has been studied for transportation vehicles. The study was carried out using the ANL-developed systems analysis code and the vehicle analysis code. The systems code includes models for the PEFC components and has been applied for steady-state and dynamic applications.

2. At the design point, the system efficiency is above 50% for a 50-kW system. The efficiency improves at partial-load and approaches 60% at 40% load. The improvement results from the fuel cell operating at lower current densities on the V-I curve. At much lower loads, the system efficiency drops because of the deterioration in the performance of the compressor, expander, and eventually the fuel cell. The system performance suffers at lower

temperatures, as the V-I characteristic curve for the fuel cell shifts downward because of the increased ohmic losses.

3. The results of the transient analysis indicate that the hydrogen-fueled PEFC system can start rather rapidly, within seconds from ambient conditions. However, the warm-up time constant to reach the design operating temperatures is about 180 s. It is important during this period for the coolant to bypass the system radiator until the coolant temperature approaches the design temperature for the fuel cell.

4. The systems analysis code has been applied to two mid-size vehicles: the near-term Ford AIV Sable and the future P2000 vehicle. The results of this study show that the PEFC system in these vehicles can respond well to the demands of the FUDS and Highway driving cycles, with both warm and cold starting conditions. The results also show that the fuel-cell AIV Sable vehicle has impressive gains in fuel economy over that of the internal combustion engine vehicle. However, this vehicle will not be able to meet the PNGV goal of 80 mpg. On the other hand, the P2000 vehicle approaches this goal with variable efficiency of the compressor and expander. It is expected to exceed that goal by a big margin, if the efficiency of the compressor and expander can be maintained constant (at 80%) over the power range of the fuel cell system.

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