PERFORMANCE REQUIREMENTS FOR A GASOLINE-FUELED AUTOMOTIVE FUEL CELL SYSTEM TO MEET THE PNGV TARGET OF 80 MILES PER GALLON

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Introduction

Fuel cells are efficient energy conversion devices and hold great promise for automotive propulsion power. To realize their full potential, however, the fuel cell stack(s) and the balance of plant must be considered together to see how the fuel cell system might be configured and operated to meet performance targets, while reducing cost and satisfying the weight, volume, and various operational constraints. One such performance target been established by the PNGV (Partnership for a New Generation of Vehicles): 80 miles per gallon of gasoline on the combined urban and highway driving schedules [1]. In this paper, we present the results of a computer simulation and analysis of the projected fuel economy of conceptual vehicles powered by gasoline-fueled polymer electrolyte fuel cells. In this analysis, we did not include fuel cell/battery hybrid systems and, thus, did not take into account any fuel economy gains achievable by, for example, regenerative braking.

The Model

For the results discussed here, we used the system design and analysis software package, GCtool, developed at Argonne National Laboratory [2]. The package includes component models (of fuel cells, reactors, fluid devices, heat exchangers, etc.), mathematical utilities (non-linear equation solver, ordinary differential equation solver, integrator, constrained non-linear optimizer), and property utilities (thermodynamic data, chemical kinetics, and multiphase equilibria). The model permits variable system configurations, recycle loops, and equality and inequality constraints. For the present study, we used GCtool to determine the fuel economy achievable with near-term components: a pressurized fuel cell system using catalytic autothermal reforming of the gasoline. We calculated the performance of an 80-kW fuel cell system used to propel three conceptual vehicles simulated on the federal urban and highway driving schedules. We also examined the tradeoffs in fuel cell size and design operating points.

System and Vehicle Parameters

Table 1 shows the major system design and operating parameters used in this analysis. All of these parameters were held constant as the fuel cell system was operated over the range of 0% to 100% of its rated power; however, the system pressure was allowed to vary with the air and fuel flow rates as they changed with the power demand on the fuel cell system. Table 2 shows the key parameters of vehicle test weight and drag coefficient for the three conceptual vehicles studied: (1) an extremely lightweight vehicle, (2) a highly aerodynamic vehicle, and (3) a very lightweight and aerodynamic vehicle. Other vehicle parameters used were similar to those for a mid-size family sedan.

Table 1. Design parameters for the fuel cell system.

Ambient temperature	27ºC, 80ºF
System pressure	3.2 atm abs
Reformer temperature	827ºC, 1520ºF
Water-to-fuel ratio	2.2 (by weight)
Fuel utilization	85%
Oxidant utilization	50%
Pump, fan efficiencies	75%

Table 2. Test weights and drag coefficients for three conceptual vehicles and their corresponding power requirements.

Parameter / Vehicle	Lightweight	Aerodynamic	Lightweight/ Aerodynamic
Weight (kg)	1043	1379	1043
Drag Coefficient	0.25	0.163	0.163
Max (Avg) Accel kW	74.6 (33.7)	93.5 (43)	72.8 (33.3)
Max (Avg) FUDS kW	27.7 (3.97)	35.2 (4.54)	27.3 (3.77)
Max (Avg) Highway kW	22.9 (8.17)	28.7 (7.68)	22.4 (6.75)

Accel: Power required to accelerate from 0 to 60 mph in 12 s
FUDS: Federal Urban Driving Schedule (part of Federal Test Procedure)
Highway: Highway Driving Schedule (Federal Test Procedure)

Table 2 also shows the calculated maximum and average power requirements for the three vehicles under the following conditions: acceleration from zero to 60 mph in 12 s, and the federal urban and highway driving schedules. As shown in the table, these three vehicles need an average of 33 to 43 kW to accelerate from zero to 60 mph in 12 s, during which time the required maximum power ranges from 73 to 94 kW. In comparison, the average power required by the vehicles on the urban and highway cycles is <5 and <9 kW, respectively, while the maximum power required on these driving cycles is about 35 and 27 kW, respectively. For a stand-alone fuel cell system, then, a rated power of 80 kW was selected for each of the three vehicles. This power would provide the desired maximum acceleration for two of the three vehicles and would be only slightly below that for the third vehicle. Of course, the power rating of a fuel cell system in a marketable vehicle would likely be based on other considerations as well, such as sustained hill climbing and high-speed passing ability. The present analysis is useful, however, for assessing the fuel economy implications of the key vehicle parameters of weight and aerodynamics.

Modeling Results and Discussion

A comprehensive system simulation with GCtool yielded the part-load voltage and current density for an 80-kW fuel cell system shown in Fig. 1. The corresponding system pressure is shown in Fig. 2. Note that at ~10 kW or less (the average power needed over the specified driving cycles), the fuel cell current densities are less than 50 mA/cm^2, and the operating pressure is less than 1.3 atm (i.e., the fuel cell operates not far from open circuit and ambient pressure).

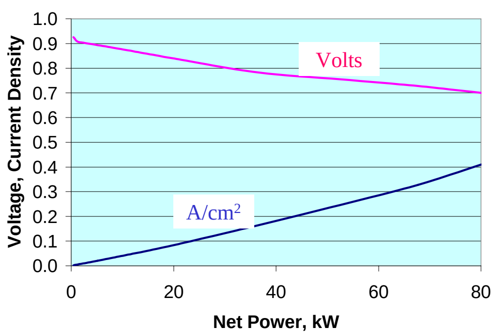

Fig. 1. Cell voltage and current density for an 80-kW fuel cell system operated at partial loads. Rated power at 0.7 V/cell.

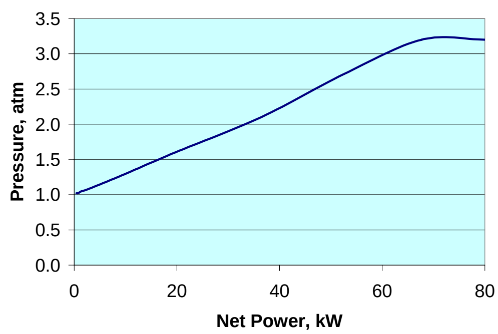

Fig. 2. Operating pressure for the 80-kW fuel cell system at partial loads. Rated power delivered at 3.2-atm pressure.

The model was applied to the three vehicles for the two driving schedules. Sample results are shown in Figs. 3–5. Figure 3 shows the second-by-second variation in the power requirement for the lightweight vehicle simulated on the highway driving cycle, as well as the average power from the beginning of the cycle. Figure 4 shows the corresponding variation in the fuel cell current density, and Fig. 5 shows the accompanying system pressure fluctuations as determined by pseudo steady-state modeling with GCtool. These three figures illustrate the rapid transients that the fuel cell power system would be subjected to under highway conditions. No attempt was made to assess the ability of the fuel cell system to respond effectively to these dynamically varying power requirements of the vehicle.

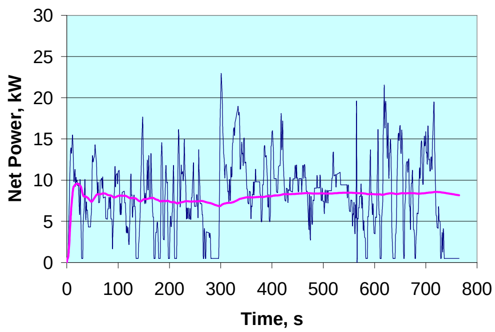

Fig. 3. Instantaneous and average power requirements for the lightweight vehicle simulated on the highway driving cycle. Maximum: 23 kW; average: 8 kW.

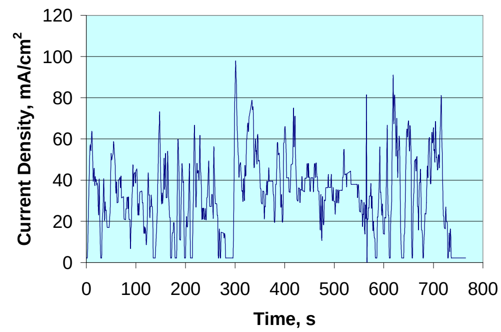

Fig. 4. Fuel cell current density for the lightweight vehicle simulated on the highway cycle. Maximum: 98 mA/cm^2; average: 33 mA/cm^2.

As mentioned above, the primary objective of this study was to determine the projected fuel economies achievable with the gasoline-fueled fuel cell system. Figure 6 gives the instantaneous and cumulative fuel consumption by the lightweight vehicle simulated on the federal urban driving schedule. As with the other variables shown in Figs. 3–5, the fuel consumption varies sharply and rapidly, and this condition would have significant implications in terms of the response of the fuel processor to the fluctuating fuel processing throughputs (as well as for the dynamic response of the other system components, such as the anode exhaust gas burner and compressor/expander).

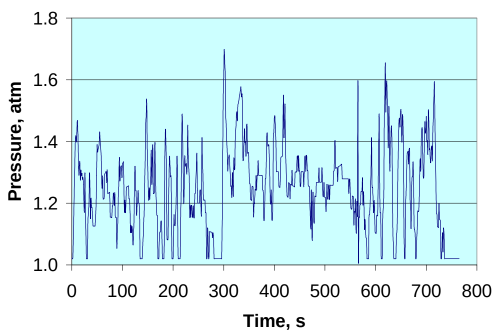

Fig. 5. Fuel cell system pressure for the lightweight vehicle simulated on the highway cycle. Maximum: 1.7 atm; average: 1.24 atm.

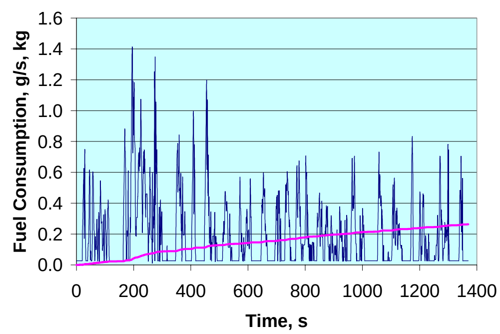

Fig. 6. Instantaneous (g/s) and cumulative (kg) fuel consumption by the lightweight vehicle simulated on the urban driving schedule.

The calculated fuel consumption determined for the different vehicles on the two driving cycles was then converted into the equivalent fuel economy in terms of miles per gallon, and the results are shown in Fig. 7. The lightweight vehicle achieves 75, 90, and 82 mpg on the urban, highway, and combined cycles, respectively. The corresponding miles per gallon for the heavier but much more aerodynamic vehicle are 65, 96, and 77, respectively. This vehicle has a poorer fuel economy in urban driving due to its higher weight, but better fuel economy on the highway due to the lower drag coefficient. These results show that reducing the vehicle weight is *essential* to meeting the fuel economy goal of $\geq$80 mpg, although reducing the drag coefficient also helps.

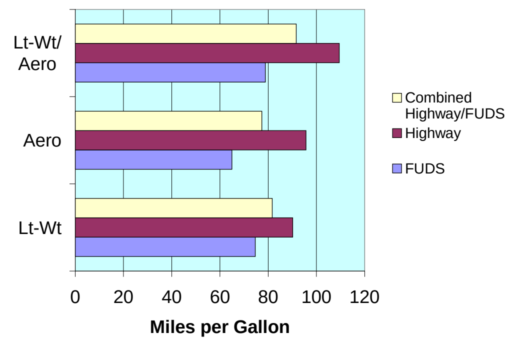

Fig. 7. Fuel economy for the three vehicles on the urban, highway, and combined driving cycles.

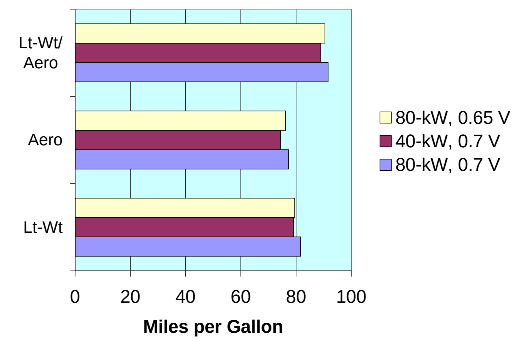

Fig. 8. Combined cycle fuel economy for the three vehicles for various combinations of fuel cell size and operating points.

The effect of using a smaller fuel cell on the combined cycle fuel economy of the three conceptual vehicles is shown in Fig. 8. For this analysis, the fuel cell size was reduced by two means. In one, the rated power was reduced from 80 to 40 kW, but the design point was maintained at 0.7 V/cell (this option would require a battery or other hybrid system to meet vehicle acceleration requirements, but the fuel cell power is still adequate to meet all of the requirements of the urban and highway driving schedules). In the other, the rated fuel cell power was maintained at 80 kW, but the design point cell voltage was reduced to 0.65 V, thereby permitting higher fuel cell power densities (in W/cm^2) and, hence, smaller active cell area and a smaller fuel cell stack. As shown in Fig. 8, each approach reduces the fuel economy slightly, by 2 to 3 mpg, such that now only the lightweight/aerodynamic vehicle still meets the PNGV goal.

Conclusions

- To achieve the PNGV goal of up to 80 mpg, a gasoline-fueled, 80-kW fuel cell vehicle will need to be extremely lightweight and reasonably-to-highly aerodynamic.
- A fuel cell system of 40 kW (or less) net power can meet the requirements of the federal urban and highway driving schedules. Other performance parameters, however, such as acceleration, hill climbing, and high-speed passing ability may dictate a higher total power "engine" for the fuel cell vehicle.
- The fuel cell is never pushed to the rated power on these drive cycles; the average power draw is ~10% of rated power, with short bursts to 35% of rated power (for the 80-kW system).
- The operating current densities are low, with an average of <35 mA/cm^2 and a maximum of <100 mA/cm^2 (for the 80-kW system). Similarly, the system operating pressures are also low, ranging between 1 and 1.7 atm for the system designed for 3.2 atm at the rated power.
- Lowering the design-point cell voltage reduces the fuel economy only slightly, but it would reduce the size and cost of the fuel cell stack significantly (however, sizes of the fuel processor and heat exchangers would increase due to the lower efficiency at the design point).

Acknowledgment

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References

1. Partnership for a New Generation of Vehicles Program Plan (draft), U.S. Department of Commerce, PNGV Secretariat, Washington, D.C.
2. "GCtool for Fuel Cell System Design and Analysis. User Documentation," H. K. Geyer and R. K. Ahluwalia, Argonne National Laboratory Report No. ANL-98/8 (1998).