SCALING OF FUEL CELL SYSTEMS FOR MICRO-POWER APPLICATIONS

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Abstract: A model for miniature direct methanol fuel cell systems was constructed and used to investigate the scaling of small fuel cell system performance. The model accounts for the scaling of component performance in order to properly represent the balance of plant. The model results indicate that a 120 gram direct methanol fuel cell system can achieve power densities in excess of 0.1 W/g and maintain this power level for several hours. Power density can be improved by decreasing the number of cells and the fuel mass fraction at the expense of reduced endurance. While this power density is approximately one order of magnitude smaller than what can be attained using a battery, the fuel cell system has much higher energy density and thus can operate for much longer periods.

Keywords: fuel cells, direct methanol, system modeling

INTRODUCTION

Fuel cell power systems that consume high energy density fuels are promising alternatives to battery-only systems for micro-power applications (< 100 W) like portable electronics and micro-scale vehicles where long endurance and rapid replenishment in the field are important. Examples of fuels that store energy much more efficiently than electrochemical materials in the best batteries are liquid hydrocarbons ($\leq$ 12.7 Wh/g), light alcohols ($\leq$ 9.0 Wh/g), and soluble hydrides (7.1 Wh/g). However, the energy density advantage of these fuels can only be realized if they are converted into useful power efficiently. While conversion efficiencies of most fuel cell membrane-electrode assemblies in and of themselves are high enough (above 20%) to realize factors of five or better improvements in endurance and/or range, the conversion efficiency of the overall fuel cell system is determined by the operating voltage and fuel utilization in the cell stack and by the parasitic losses associated with fluid pumping, fuel pre-processing (as needed), thermal management, and power conditioning. These parasitic losses become more significant with decreasing fuel cell size because of increased surface/volume ratio and can reduce or even eliminate the advantage of using high energy density fuels in small-scale systems.

The objective of this work is to develop a modeling framework for an entire fuel cell system that accurately represents how fuel cell stack performance and parasitic losses vary with design. Thus, realistic performance assessments of small-scale fuel cell systems can be made. While some system studies have been performed for small-scale power applications [1], they often assume component efficiencies based on larger applications. The approach here is to develop physics-based component models that capture scaling of pumping, resistive, and other losses as system size and power output decrease.

The model presented here is for a direct methanol fuel cell (DMFC). A DMFC is chosen because it is one of the simplest low temperature cells capable of consuming liquid fuels and simplicity tends to result in relatively low mass systems suitable for use in miniature ground vehicles and aircraft. The overall system efficiency η_{th} is characterized by two parts: the fuel cell stack efficiency η_{FC} and the overall balance of plant/power efficiency, η_{BOP} (which equals the 1 – the fraction of fuel cell power used to run the parasitic loads). Thus, η_{th} can be written as the product of the two sub-system efficiencies.

SYSTEM MODEL

Figure 1 is a schematic illustration of the fuel cell system being modeled. A pump feeds fuel to the anode and a fan supplies air to the cathode. The air provides the oxidizer and is flowed at a high enough stoichiometric ratio to serve as coolant for the stack. The air flow rate is controlled to maintain the fuel cell at a stable operating temperature of 57 °C. The fuel is stored in an external fuel tank as a concentrated solution of methanol in water (8.3% by mole methanol or 5 M solution). A DC-DC converter boosts the low voltage DC power from the DMFC stack into a higher bus voltage (24 VDC) used to run the parasitics and provide external load power. The DC-DC converter efficiency is assumed to be constant at 93%.
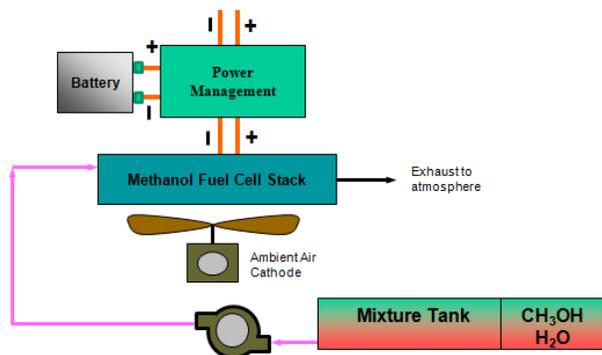
Fig. 1: Direct methanol fuel cell model system.

The system model derives from one developed for a larger system that incorporated a liquid hydrocarbon reformer that produces hydrogen for a polymer electrolyte membrane (PEM) fuel cell [2]. An iterative model solves the mass and energy balances for each component. The simulation begins by specifying a desired net power output of the system. The fuel cell stack design/architecture is based on the work of Hwang et al. [3]. A voltage vs. current density (i.e., V-i) curve is adopted from the performance reported in [3], and the baseline open-circuit voltage is adjusted based on average concentrations of fuel and air in the anode and cathode respectively. The current density i of the stack is solved for iteratively to meet the instantaneous power demand based on the specified external load and the power required to meet the parasitic loads. The fuel flow rate is determined by performing a species balance on the anode feed to satisfy the methanol demand at the desired stoichiometric ratio – 1.3 in this study. The stoichiometric ratio equals the inverse of stack fuel utilization (77%), which is non-zero in order to avoid damage to the stack due to inadequate fuel supply near the end of the anode flow path.

Since the stack is air cooled, the total air flow rate is determined by performing a cathode species balance on the cathode side and an energy balance on the entire stack. Separate mass and energy balances are subsequently performed on all other components in the system to determine the flow rates through each and the associated parasitic losses. The gross power output of the fuel cell (ie. the usable power requirement plus the parasitic power losses) is updated, a new stack operating voltage is selected to meet this demand, and the process is repeated until the stack voltage has converged. The model is implemented in MS Excel using a Visual Basic program running as a macro.

Empirical data on how the performance of fuel cell stacks, pumps, and blowers scale with size are used to estimate the mass and volume of each component of the system. The total mass or volume of the fuel cell system is the sum of the fuel cell components mass (m_{tot}) or volume (V_{tot}) plus the mass (m_{fuel}) or volume (V_{fuel}) of the fuel and fuel tank.

The scaling of the fuel cell system's performance was investigated by varying two parameters in the model: net power output and the number of electrochemical cells in the fuel cell stack. Net power output was varied between 5 and 45 W, and the number of cells between 5 and 35. In the current system, cell area was held fixed at 10.9 cm^2 based on the previous study [3]. By increasing the number of cells for a particular system, the current density decreases thereby increasing cell voltages and improving the stack efficiency η_{FC}. However, this comes at an increased system size. This results in a trade-off for energy density due to increasing system size and decreasing specific fuel consumption.

As the power requirement increases, the required airflow may exceed the capability of the fan. In this case, the code automatically replaces the fan with a larger one. Three fans from Risun Expanse Corp [5], Jarothermal [6], and Indek [7] are incorporated in the model. The performance of all components (like fans) is represented using data given by researchers or manufacturers. A single fuel pump is used for all simulations. It is made by TCS Micro Pumps Ltd. [4].

RESULTS & DISCUSSION
System Efficiency

Figure 2 shows how system efficiency η_{th} varies with the total mass m_{tot} of the fuel cell system minus fuel and tank. The numbers at the ends of each curve give the number of cells in the stack at those points. The number of cells varies linearly along the curves between the end points, and as expected, η_{th} increases with the number of cells because the current density decreases with increasing number of cells. However, the improvement in efficiency is non-linear and decreases with increasing numbers of cells. The effect of this trend on power and energy density will be discussed shortly.

Figure 2 also shows that decreasing the power requirement does not change the peak attainable efficiency until the power drops below 10 W. At 5W, the baseline parasitic losses associated with the pump and blower are more important than the ohmic losses and the peak attainable efficiency is lower. This is the reason that the 5W curve crosses the others.
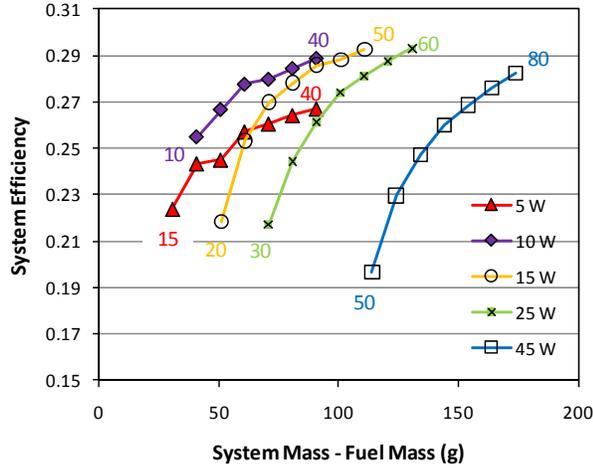
Fig. 2: Fuel cell system efficiency vs. the mass of the system less fuel for different overall power levels. The numbers at the ends of the curves indicate the number of electrochemical cells in fuel cell stack.
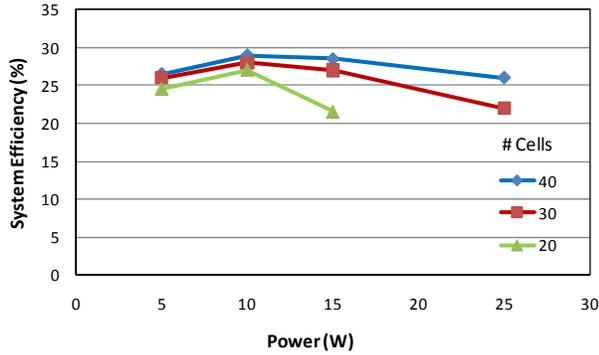

Fig. 3: Fuel cell system efficiency vs. power output.

Figure 3 shows that efficiency is maximized at intermediate powers when the number of cells in the fuel cell stack is fixed. This optimum is a result of the tradeoff between stack overpotential losses that increase with power and baseline parasitic losses that decrease in percentage with increasing power. Figure 3 suggests that the power level associated with peak efficiency does not depend on the number of cells in the stack, but this result is only for a range of 20 to 40 cells. In general, it is expected that the peak in this curve will move to higher powers with more cells.

Power and energy density

Up to this point, the discussion has focused on everything associated with the fuel cell system except the fuel and fuel tank. This was done in order to highlight the critical aspects of the fuel cell design. However, the power and energy density of the entire system are heavily influenced by the fuel mass fraction (ζ) which is defined as the ratio of the mass of fuel+tank (m_{fuel}) to the mass of the fuel cell stack

and balance of plant combined ($m_{FC} + m_{BOP}$). Thus, total system mass m_{tot} equals $m_{FC} + m_{BOP} + m_{fuel}$, and power and energy density of the system are given by:

$$\frac{P}{m_{tot}} = \left(\frac{P}{m_{tot}}\right)\frac{1}{1+\zeta} \qquad (1)$$

$$\frac{E}{m_{tot}} = \eta_{th}Q_R \frac{1}{1+1/\zeta} \qquad (2)$$

In these equations, P/m_{tot} is the power density of the system without fuel, Q_R is the energy density of the fuel-water mixture (2914 J/g for the 5 M methanol solution). P/m_{tot} represents the maximum power density achievable in the system and $\eta_{th}Q_R$, represents the maximum possible energy density.

The maximum possible power density of the fuel cell system is shown in Figure 4 as a function of m_{tot}. Decreasing the number of cells increases power density for all configurations considered. It should be pointed out, however, that more work is needed to identify the upper end points of these curves which are set by the maximum possible power output of a single fuel cell.
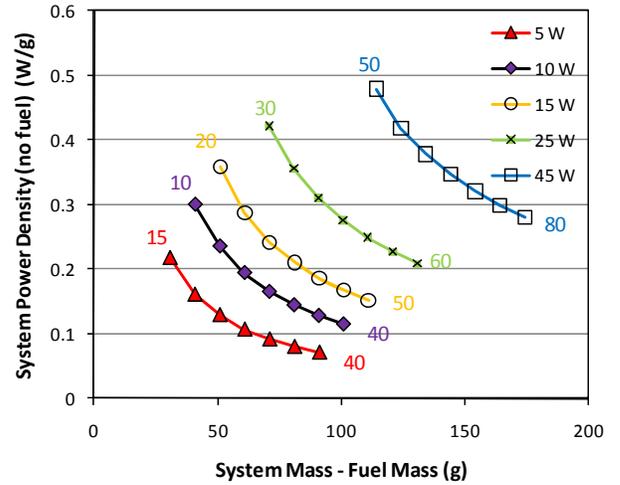

Fig. 4: Maximum power density of DMFC system at various power demands. Numbers at ends of curves give number of electrochemical cells in fuel cell stack.

The functions of ζ that modulate the expression of these maxima in the complete system are plotted in figure 5. Their behavior as ζ is increased indicates that will be necessary to trade power density for energy density (or endurance). $\zeta=1$ seems to represent a reasonable compromise where both power density and energy density are impacted equally.

The complete tradeoff between power and energy density is illustrated in Figure 6. It shows power density as a function of system energy density for three 10 Watt direct methanol fuel cell systems based
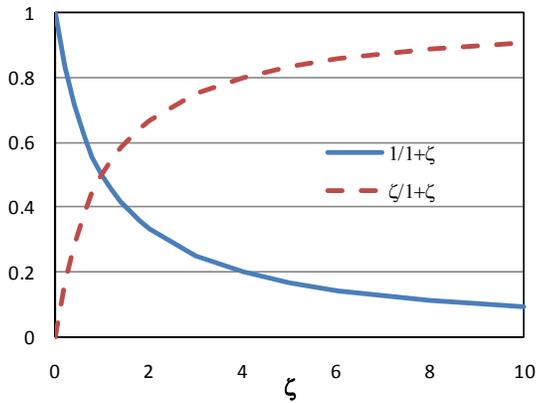
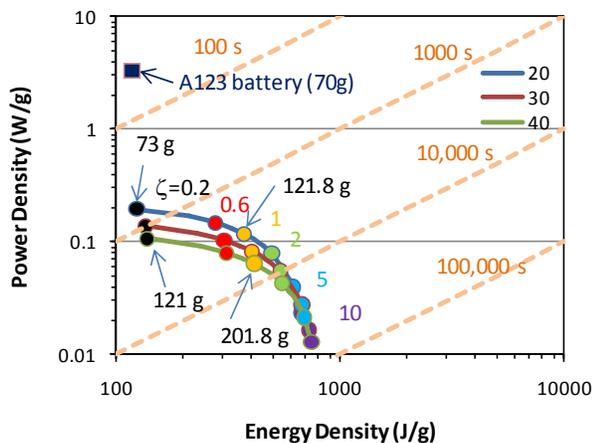*Fig. 5: Functions of ζ that modulate the peak power and energy density of the fuel cell system.*

Fig. 6: Ragone plot for a series of 10 W fuel cell systems.

on 20, 30 and 40 cells. The solid symbols correspond to systems with different values of ζ. The dashed diagonal lines show contours of constant endurance. m_{tot} of a few systems are provided for reference. As ζ becomes large, most of the system's mass is contained in the fuel and the system performance curves approach the energy density of methanol times the conversion efficiency. As ζ becomes small, power densities approach the maxima but this comes at the price of reduced endurance because there is less fuel available. The curves cross because systems with more cells have lower power densities but are somewhat more efficient. Finally, a symbol corresponding to a high performance Li-ion battery from A123 Systems is provided as a reference. While the battery's power density is much higher than can be attained by the fuel cell systems, its endurance is comparable to a fuel cell system with comparable mass and is much lower than fuel cell systems that are only moderately heavier.

CONCLUSION

A model for a direct methanol fuel cell system was constructed and used to investigate the scaling of small fuel cell system performance. The model is unique in that it accounts for the scaling of component performance in order to properly represent the balance of plant. The model showed that a 120 gram direct methanol fuel cell system can achieve power densities in excess of 0.1 W/g and maintain this power level for several hours. Power density can be improved by decreasing the number of cells and the fuel mass fraction at the expense of reduced endurance.

FUTURE WORK

Future work will focus on adding an anode recirculating loop such that pure methanol can be stored in the fuel tank. This will increase fuel energy density and thus the endurance by more than a factor of five.

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