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Hydrogen Fuel Cells for Small Unmanned Air Vehicles

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Abstract

The Naval Research Laboratory has developed hydrogen fuel cell propulsion systems for unmanned air vehicles (UAVs). The high electrochemical conversion efficiency of fuel cells combined with the high specific energy of H_2 fuel makes them suited to extending the endurance of small UAVs. The major consideration for UAVs is sufficient system level specific power (W/kg) for take off and high specific energy (Wh/kg) for long endurance. The high specific power is gained from using high power fuel cells and keeping components lightweight. The high specific energy comes from high weight fraction H_2 fuel storage combined with a high efficiency fuel cell. The fuel cell air compressor and heat exchanger and the H_2 storage system are major weight contributors, thus making them lightweight is critical to the vehicle design.

Introduction

The attributes of hydrogen fuel cells for propulsion are well known: proton exchange membrane fuel cells (PEMFCs) convert hydrogen and oxygen to water electrochemically, providing a direct current source of electricity for an electric power train and auxiliary loads. They respond rapidly to changes in load, making them well matched to the dynamics of vehicle loads. The high energy per unit weight of H_2 gas combined with high-energy electrochemical conversion efficiency of PEMFCs affords high energy per unit weight and volume, resulting in longer endurance than present battery systems. Accordingly, hydrogen fuel cell propulsion is the subject of billions of dollars of commercial investment world wide for automobiles.

The features that make hydrogen fuel cells attractive for automobile propulsion also make them attractive for unmanned air vehicles (UAVs). Furthermore, unmanned air vehicles do not carry pilots or passengers and do not operate on public roads, so less stringent safety constraints are required. The main difference between hydrogen systems for automobiles and for air vehicles is the high power to weight ratio required to keep air vehicles aloft. Remaining airborne thus mandates a relatively high power to weight, or high specific power (W/kg) system. High specific energy (Wh/kg) is required for both automobiles and air vehicles because it is proportional to endurance. Power density and energy density (W/L and Wh/L, respectively) are also important because they control the amount of volume occupied by the system.

Our team at the Naval Research Laboratory (NRL) has been studying the applicability of hydrogen fuel cells to UAVs in the range of 6 to 35 kg vehicles that require 300 to 3 kW fuel cells, a power range where large batteries would be needed for electric propulsion, and the only available combustion engines are relatively inefficient and unreliable. Representative air vehicles in this size range include Aerovironment's Puma and Insitu's ScanEagle. Our specific focus has been on extending endurance, which demands a focus on the specific energy of the system. Our primary experimentation vehicle is the Ion Tiger UAV, a custom platform that has been described in prior publications (1, 2).

A photograph of the 16-kg Ion Tiger is shown in Figure 1. Long endurance fuel cell powered flights have been carried out on the Ion Tiger using a ~550-W, 1.1-kg PEMFC system built by Protonex Technology Corporation. The system was integrated directly to an electric motor without a hybrid battery. Two fuel systems have been compared: one with high-pressure gaseous H_2 (GH_2) (1,2) and the other with liquid hydrogen (LH_2) (3,4). The GH_2 fuel system comprised 500 g of H_2 stored at 5000 psi in a 4-kg type-III carbon overwrapped pressure vessel (COPV) with a lightweight pressure regulator. With GH_2, we recorded 23 and 26-h flights in 2009 while carrying ~2 kg of payload. The endurance difference was the result of calmer weather during the 26-h flight, which lowered the power draw and energy demand of the mission. A 48-h flight of the Ion Tiger was accomplished in in 2013 using a LH_2 system storing 1323 g of cryogenic hydrogen in a 4-kg aluminum dewar.

This paper will illustrate some of the considerations that are important for development of fuel cell systems for a practical, long endurance UAV.

Figure 1. Ion Tiger UAV in flight. The Ion Tiger gross takeoff weight (GTOW) is 16 kg, with 40% of its weight budget allocated to the propulsion/energy system. The wingspan is 5.2 m, with a lift over drag ratio near 17 (2). The inset shows the Ion Tiger's 1.1 kg ~550W fuel cell system built by Protonex Technology Corporation.

Fuel Cell System Design Considerations

A fuel cell system for a long endurance UAV must first be designed to have sufficient power for take off and climb out, and then carry enough H_2 fuel for long endurance. The weight budget for the propulsion system is typically 40% of the vehicle gross takeoff weight (GTOW) and is split between the fuel cell system and the hydrogen storage. Within that budget, a long-endurance UAV requires a light and efficient fuel cell system with most of the weight budget for hydrogen storage.

A generic schematic of a liquid-cooled fuel cell system in shown in Figure 2, and variants can be found elsewhere (5,6). The system contains a fuel cell stack with its balance of plant (BOP) along with the H_2 fuel tank. The key attributes for design include the following interrelated parameters: (a) the stack voltage, efficiency and power output, (b) the air compressor flow rate, pressure rating, and power draw, and (c) the heat exchanger (HEX) heat transfer capacity and size.

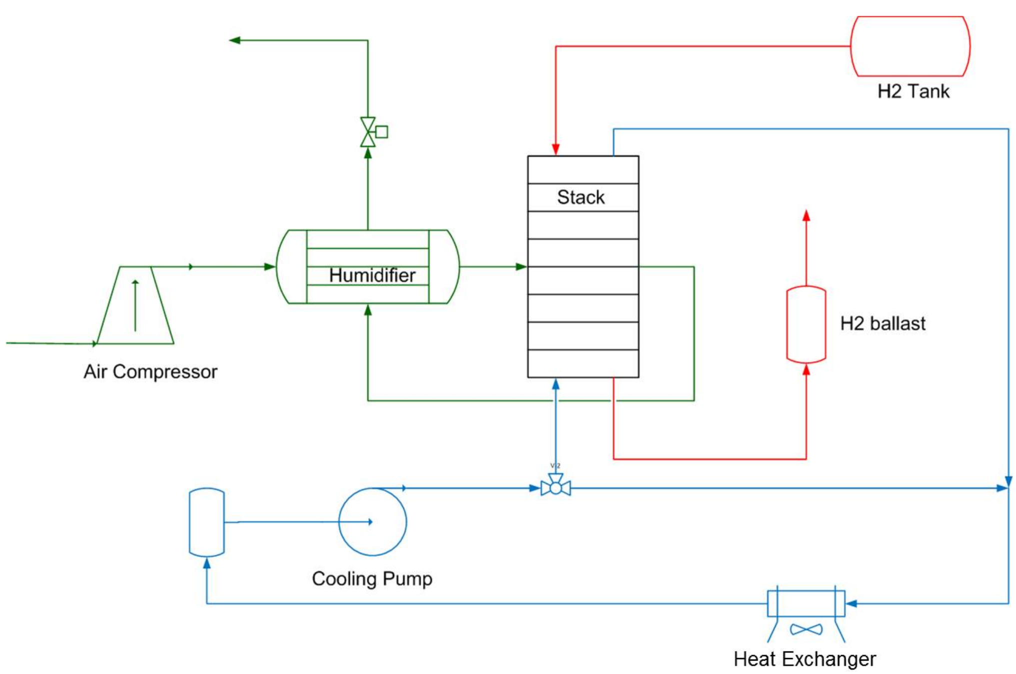

Figure 2. General schematic of a fuel cell system. The sizing of the system is determined largely by the interrelated properties of the stack, compressor and radiator.

Flight data from the Ion Tiger is shown in Figure 3. The fuel cell experiences the highest power demand of nearly 600 W during the first part of its flight as it is climbing continuously. Over the course of the flight, the power demand for propulsion drops to 200 W as the vehicle catches thermals or follows a tail wind. In the case of this flight, the vehicle also flew for several hours at full power in the middle of the flight as windy conditions prevailed. Direct drive off of the fuel cell system allowed long periods of flight at very low power or high power. For some applications, such as vertical take off and landing (VTOL) in helicopters, even higher power would be needed at take off, plus high power at landing (6).

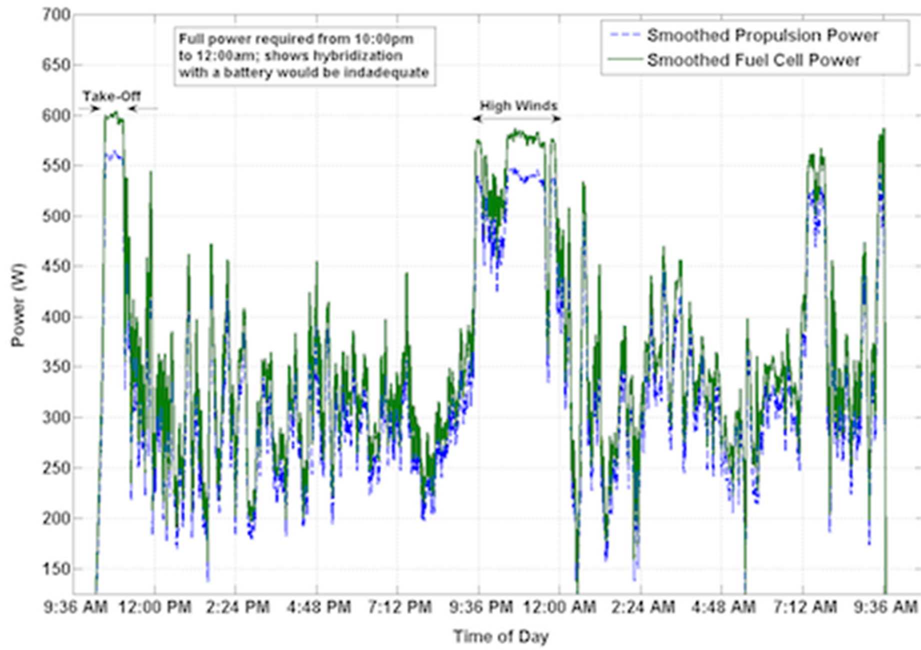

Figure 3. Power profile of the Ion Tiger UAV on a 23-h fuel-cell-powered flight, consuming approximately 500 g of H_2. Adapted from reference (2).

The electrical efficiency of the fuel cell is proportional to the ratio of the operating voltage of each cell, V_{cell}, to the thermodynamic open circuit value of formation of H_2O from O_2 and H_2. The theoretical OCV is nominally 1.23 V at standard temperature and pressure and when using the lower heating value for H_2O (7), as in Eq. [1].

$$\text{Cell electrical efficiency} = \frac{V_{cell}}{1.229} \qquad [1]$$

The operating cell voltage deviates from the thermodynamic value due to overpotential and entropic ($T\Delta S$) losses that occur in the electrochemical conversion of H_2 and O_2 to H_2O. The largest overpotential loss is caused by the inefficient oxygen reduction reaction on the cathode catalyst (typically nanoscale Pt on carbon). Additional contributors to the overpotential losses are mass transport and ohmic losses, which dominate at high current densities. The overall fuel cell system efficiency is determined by the cell electrical efficiency minus electrical losses used to operate the BOP. Whatever energy from the H_2-to-H_2O conversion that does not create electrical energy is converted to heat, so a 50% efficient fuel cell system will convert 1000 Wh of H_2 (~29 g of H_2) into 500 Wh of net useable electricity and 500 Wh of heat dissipated by the stack and supporting BOP.

The fuel cell stack in the ~550-W system weighed about 0.5 kg, or >1000 W/kg. The stack power output is a function of the current density, or power density, per unit active area of each membrane electrode assembly (MEA) in the stack. Optimizing MEA current density has been a massive undertaking by the entire fuel cell community for decades and has centered around increasing catalyst activity, decreasing the membrane resistance, optimizing gas flow through the cell flow fields, and controlling O_2 and H_2O mass transport through the porous gas diffusion layers (7).

Assuming that the stack has suitable flow fields for gas and water transport, the performance of the MEAs must be coupled to the air blower or compressor that distributes air to the MEA cathodes. The power density of the MEAs generally increases with increasing air pressure, but there is also an energy penalty for driving the compressor. An example of the data used for such an optimization is shown in Figure 4 where the net power from a commercial MEA is compared to its electrical efficiency for a range of cathode air pressures. At 0 kPa (i.e. ambient pressure), the MEA has the highest efficiency low power, but then with increasing power it becomes far less efficient than the MEAs operating under pressure. Likewise the MEA tested at 150 kPa produces the most power efficiently at high power, but has far inferior efficiency at low power. There is also an increased weight penalty for a larger compressor.

Given the flight profile in Figure 3, where the vehicle spent most of its time operating at 280 to 300 W vs a max power of 580 to 600 W, the fuel cell system should be designed to be most efficient near the half-point of its peak power, or 50 to 75 kPa.

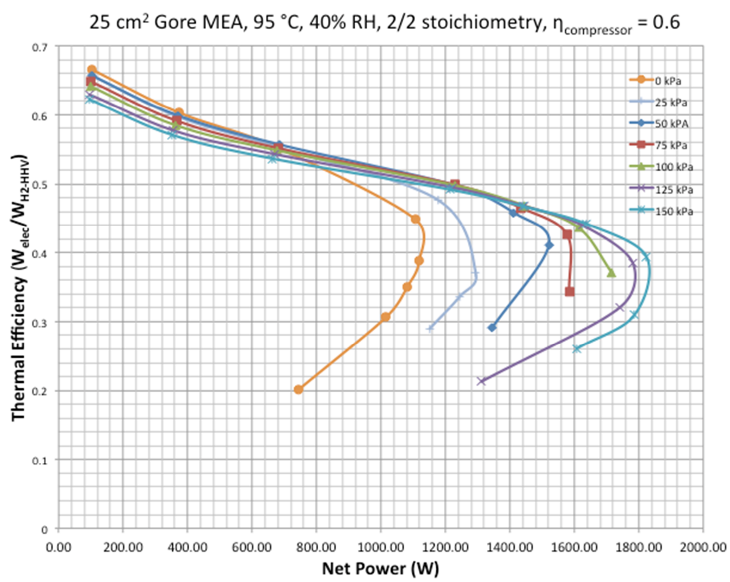

Figure 4. Thermal efficiency of a fuel cell vs. net power output as a function of pressurization. Results are measured for a 25 cm^2 WL Gore catalyzed coated membrane with SGL gas diffusion layers.

A small HEX is also desirable to minimize the weight, volume and air drag of the system. A practical UAV will likely experience temperatures of 40 to 50 °C during preflight preparations – we routinely measure tarmac temperatures well in excess of 45 °C in our testing sites in Southern Maryland during the summer. We had inadequately sized radiators in our early flight testing, leading to inadequate cooling and early landings, which prompted us to carefully study vehicle HEX sizing (8).

The impact of stack-external air temperature difference on HEX size is shown in Figure 5, assuming a standard aluminum fin-and-tube HEX. This calculation is based on Newton's law of cooling, whereby the rate of heat rejection is proportional to the average temperature difference between the HEX and ambient air, as written in Eq. [2].

$$dQ/_{dt} = h\,A[T(t)_{HEX} - T_{ambient}] \qquad [2]$$

In Eq. [2], Q is the rejected thermal energy (J), t is time (s), h is the convective heat transfer coefficient (W m^{-2} K^{-1}), A is the surface area of the HEX (m^2), $T(t)_{HEX}$ is the time dependent heat of the HEX, and $T_{ambient}$ is the temperature of the external air. Rearranging Eq. [2] to Eq. [3] shows how HEX area depends on the rate of heat rejection, the temperature difference between the HEX and the ambient conditions, and the heat transfer coefficient. Size and weight both scale linearly with area for a traditional tube-and-fin HEX.

$$A = \frac{dQ/_{dt}}{h\,\Delta\,T(t)_{HEX-ambient}} \qquad [3]$$

According to Eq. [2] and shown in Figure 5, the HEX size is minimized by reducing the rate of heat rejection and increasing the temperature differential between the system and the environment. Raising the air flow rate through the radiator can also increase *h*, thereby decreasing the necessary radiator area, but this incurs a greater drag penalty. Similarly, further cooling can be achieved by blowing air over the fuel cell stack at the expense of additional drag. While average values for *Q*, $\Delta T_{HEX\text{-}ambient}$ and *h* are sufficient to obtain rough approximations for the necessary radiator area, a more accurate estimate can be developed using a detailed stack model to estimate *Q*, $\Delta T_{HEX\text{-}ambient}$ and *h* for the expected vehicle flight profile. Such a model should consider the liquid/vapor ratio of the exit water (indicting the rate of latent heat rejection) plus the rate of convective heat loss from the PEMFC stack (5, 7).

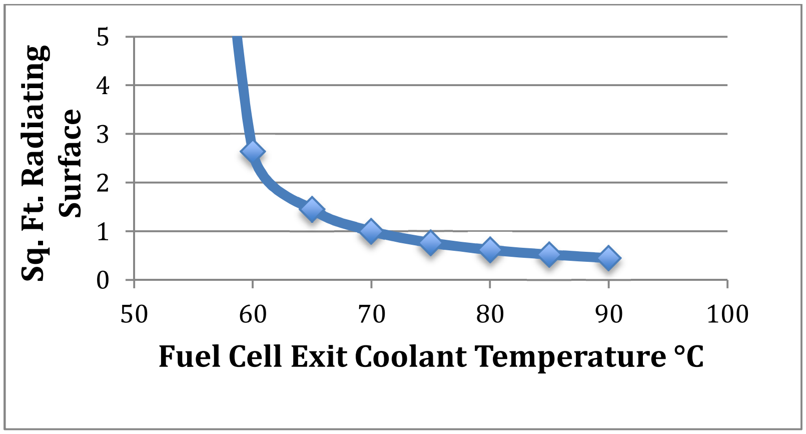

Figure 5. Estimation of amount of surface area required for an aluminum HEX vs the exit temperature of the coolant from the fuel cell stack at an ambient temperature of 49 °C. The size of the HEX is prohibitively large for a fuel cell that operates below 70 °C.

Figure 5 shows that a small HEX can be used only when the fuel cell can operate at >15 °C greater than the external temperatures, so a PEMFC stack capable of at least 65 °C operation is desired. The HEX is further minimized by using a stack that is electrochemically efficient and produces more electricity than heat, plus a stack that is capable of operating at high temperatures. Thus the push for stacks with high efficiency for the oxygen reduction reaction and > 60 % electrical efficiency (with the remaining 40% rejected to heat) and high temperature operation of > 90 °C. Inefficient low temperature fuel cell systems, such as direct methanol or biological one, are likely inadequate for vehicle propulsion because they would need impractically large radiators. Low cost fuel cell systems using inefficient catalysts (e.g., platinum free) are also not attractive for propulsion because of the additional heat rejection requirements caused by their low electrical efficiency.

The electrical efficiency of the fuel cell system also plays a direct role in the vehicle endurance. Figure 6 shows the weight distribution for the 550-W Ion Tiger hydrogen fuel cell system that flew for 23-26 h using 500 g of GH_2 stored at 5000 psi in a COPV (2). The fuel cell system (with the compressor and electronics) weighed 1.2 kg, comprising less than 20% of the full hydrogen fuel cell system weight. The weight distribution is similar in the vehicle that flew for 48 h with LH2, except that it carried 2.5 × more H_2 (3,4). The total weight of the system is 6.9 kg, yielding a specific power of 80 W/kg at the full system level. The specific energy of the Ion Tiger was 1170 Wh/kg for the system with 500 g of 5000 psi H_2 flown for 26 h. For the LH_2 system, more H_2 was carried bringing the initial system weight to 7.8 kg. The specific energy from the 48 h LH_2 flight 1770 Wh/kg. The flight's specific energy was lower than expected due to higher-than-expected heat leak into the H_2 dewar, causing H_2 to be vented overboard (4).

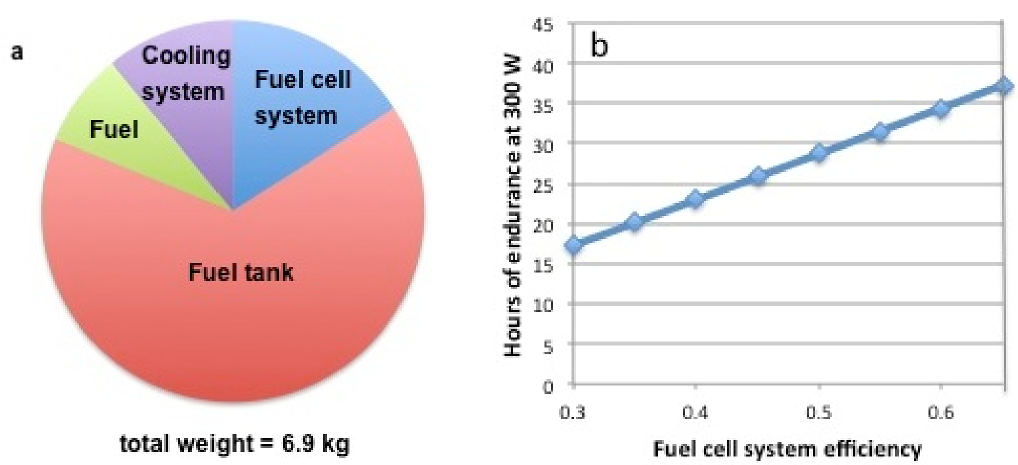

Figure 6. (a) Weight distribution of components of the hydrogen-fuel cell system for the Ion Tiger flown on 500 g of GH_2 stored at 5000 psi in a COPV; (b) calculated hours of flight on 500 g of GH_2 at 300 W vs. fuel cell system efficiency.

Figure 6a clearly shows that the hydrogen storage system dominates the total system weight. Figure 6b illustrates that the efficient conversion of the hydrogen to electricity by the fuel cell is critical to endurance and also an effective weight budget. Only 17 h of flight achieved for a 30 % efficient system but 37 h is possible for one that has 65% electrical efficiency. The Ion Tiger fuel cell system was 45 to 50% efficient over the full range of the flights, but new fuel cells systems with claims of higher efficiencies will contribute toward longer flights.

Note that no additional energy storage system (e.g., lithium ion battery) is included in the Ion Tiger fuel cell propulsion system. Any weight allocated to additional energy storage would consume part of the weight budget for H_2 storage, and our analyses showed that a hybrid Li-ion battery plus its associated electronics would not contribute effectively to the system efficiency. While Li-ion batteries might be beneficial on other systems for load leveling, impedance filtering, and high power operation, we found that they did not improve the overall system efficiency and thus were excluded.

As discussed above, the hydrogen system dominates the weight and volume of the hydrogen fuel cell system for the UAV. Air vehicles constrain both storage weight and storage volume, so both parameters must be considered when attempting to maximize the stored energy for a vehicle. The desire for high specific weight competes against the limited storage volume favoring compression of the gases into a smaller space. Raising the storage pressure of H_2 gas increases the storage density, but only to a point. Eventually, increases in pressure require thicker storage vessel walls to contain the pressure, and the wall thickness can grow quickly enough to obviate the greater H_2 storage. The tradeoff between pressure and storage volume is shown in Figure 7 for a notional fuselage space that is 11 inches in diameter and 16 inches long. The specific energy of the H_2 storage system decreases with weight as the wall thickness increases with increasing internal pressure, according to the maximum allowable hoop stress using the thin wall equation. While the specific energy of the hydrogen system decreases with increasing pressure, the amount of H_2 that can be stored in the 11" diameter and 16" long tank increases with pressurization.

The H_2 tank must be designed in close consideration of the available volume in the vehicle, the vehicle dynamics, and the vehicle endurance, as the vehicle fuselage diameter will affect the vehicle drag and thus power for flight. Increasing the H_2 storage-tank diameter incurs a clear penalty on the vehicle dynamics as the fuselage width and the frontal area grow. These penalties must be traded against the efficiency of storing GH_2 in a lightweight COPV, with the goal of a high specific energy H_2 system.

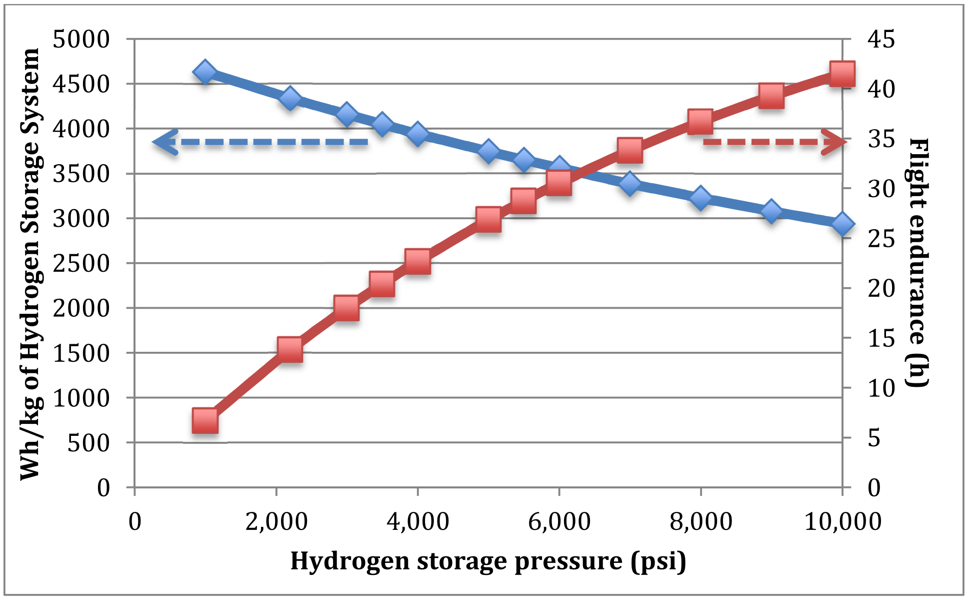

Figure 7. Trends for specific energy and flight endurance of GH_2 stored at high pressure in COPVs. The calculations are based around GH_2 stored in a notional 11” diameter COPV that is 16” long. The flight endurance assumes an average of 50% efficiency at 300 W from the fuel cell system.

Summary

This paper summarizes some of the considerations important for sizing a fuel cell system for a UAV. The major consideration is that the system has sufficient power to get the vehicle aloft, but it must also carry adequate hydrogen and be efficient for long endurance. Necessary tradeoffs include compressor power consumption vs. weight and stack maximum power vs. weight. The fuel cell system must also be capable of operation over 70 °C for effective heat rejection and efficiently convert the chemical energy in the H_2 to electrical energy. Using the results from practical fights along with stack performance, a custom BOP can be designed to maximize the opportunity for UAV flights. Further trade offs can be made around the vehicle design to optimize hydrogen storage while reducing frontal drag. These results can also be used to develop a more comprehensive power train model around a high performance, low drag vehicle.

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