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Design of a Reconfigurable Liquid Hydrogen Fuel Tank for use in the Genii Unmanned Aerial Vehicle

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Abstract. Long endurance flight, on the order of days, is a leading flight performance characteristic for Unmanned Aerial Vehicles (UAVs). Liquid hydrogen (LH2) is well suited to providing multi-day flight times with a specific energy 2.8 times that of conventional kerosene based fuels. However, no such system of LH2 storage, delivery, and use is currently available for commercial UAVs. In this paper, we develop a light weight LH2 dewar for integration and testing in the proton exchange membrane (PEM) fuel cell powered, student designed and constructed, Genii UAV. The fuel tank design is general for scaling to suit various UAV platforms. A cylindrical vacuum-jacketed design with removable end caps was chosen to incorporate various fuel level gauging, pressurizing, and slosh mitigation systems. Heat and mechanical loadings were modeled to compare with experimental results. Mass performance of the fuel tank is characterized by the fraction of liquid hydrogen to full tank mass, and the insulation performance was characterized by effective thermal conductivity and boil-off rate.

Keywords: Liquid hydrogen, boil-off, Isogrid, UAV, cryogenic tank.

INTRODUCTION

NASA has identified long endurance flight, on the order of days, as a leading flight performance characteristic for Unmanned Aerial Vehicles (UAVs) [1]. Liquid hydrogen (LH2) is well suited to providing multi-day flight times with a specific energy 2.8 times that of conventional kerosene based fuels. However, no such system of LH2 storage, delivery, and use is currently available for commercial UAVs. To our knowledge, Aerovironment’s Global observer, Boeing’s Phantom Eye, and the Naval Research Laboratory’s Ion Tiger are the only UAVs currently fueled with LH2 and specifics on the fuel tank designs are closely guarded. In general, designers of storage dewars for aircraft must consider minimizing heat transfer due to convection through the use of vacuum jacketed designs, whereas cryogenic storage systems for spacecraft often rely on the vacuum of space and typically consider heat loads from conduction and radiation only. Earth-to-orbit launch vehicles using cryogenic propellants typically use no more than spray on insulation and can be fueled on the launch pad. Boil-off is not a concern for first stage launch vehicles due to consumption rate outpacing potential boil-off due to heat leak. Due to these differences, LH2 storage for aircraft is not simply a matter of transferring existing launch vehicle storage technology [2].

Our aim is to develop an easily reconfigurable, lightweight storage tank for Technology Readiness Level (TRL) advancement through flight testing of liquid hydrogen storage and fueling technologies. Areas we intend to investigate include slosh mitigation, passive pressure regulation through ortho-parahydrogen conversion, accurate fuel level determination that is not affected by vehicle attitude (e.g. pitch and roll), and advanced insulation techniques. The resulting system design must be light-weight and geometrically tolerated for incorporation into the Genii UAV fuselage (Fig. 1) and payload envelopes.

FIGURE 1. Genii takes off for second battery powered test flight over northern Idaho.
MATERIALS & METHODS

Dewar Design

The cryogenic dewar design was primarily constrained by two factors: mass and cost. Unlike traditional lab based cryogenic dewars and experimental apparatus, our storage dewar design was governed by the necessity to reduce mass to the maximum extent possible while retaining sufficient structural integrity; minimizing mass reduces power requirements while increasing the payload capacity of the UAV. While composite materials are widely used in structural applications due to their superior strength-to-weight ratios, manufacturing methods require a high degree of skill and precision if they are to be used for pressure vessels. This degree of skill placed cost and fabrication of class IV and V composite tanks outside the capability of the student team; instead, we chose 6061-T6 aluminum for the inner and outer pressure vessels. Aluminum 6061-T6 is negligibly susceptible to hydrogen embrittlement [3] and has been previously analyzed for LH2 fuel tanks in long endurance UAVs (2014-T6 alloy) [4]. All machining was conducted in house, the majority of which was completed by an undergraduate mechanical engineering student. The vacuum vessel measures 61 cm long and 20 cm in diameter, while the inner cryogenic tank measures 52 cm long and 15 cm in diameter. Total mass of the storage dewar is 6.3 kg (excluding Multi-Layer Insulation (MLI)) with major components itemized in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenic tank</td>
<td></td>
</tr>
<tr>
<td>cylinder</td>
<td>2.06</td>
</tr>
<tr>
<td>cap</td>
<td>0.2</td>
</tr>
<tr>
<td>Vacuum tank</td>
<td></td>
</tr>
<tr>
<td>cylinder w/ flanges</td>
<td>1.18</td>
</tr>
<tr>
<td>cap</td>
<td>0.35</td>
</tr>
<tr>
<td>Baffle system</td>
<td>0.18</td>
</tr>
<tr>
<td>Liquid hydrogen tube system</td>
<td>1.01</td>
</tr>
<tr>
<td>Vapor extraction tube system</td>
<td>0.28</td>
</tr>
<tr>
<td>G10 supports</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The dewar also needs to be easily disassembled for reconfiguration to use for flight testing cryogenic hydrogen fueling technologies. Consequently, welded tank designs were avoided and removable end caps for the inner cryogenic vessel and outer vacuum vessel were chosen instead. Flat plates are the easiest configuration to machine and use for removable end caps, but are not as efficient (using a strength to weight metric) as hemispherical shells for withstanding equivalent pressure. Drawing on work conducted in the 1970s by McDonnell Douglas, an Isogrid structure [5] was developed for the end caps. Isogrid structures effectively increase the strength of a flat plate or cylindrical shell by machining a triangular grid into the material, the grid acting as a truss structure (Fig. 2). Using this approach, we designed end caps with 1.27 mm skin thickness, 1.02 mm web thickness and a mass of 0.2 kg that will be proof tested to 317 kPa (absolute pressure unless otherwise noted) for safety, while maximum overpressure will be limited to 232 kPa. Because hoop stress in the thin-walled cryogenic cylinder is the limiting case, we initially designed to 50% of the yield stress (at 20 K, \( \sigma_{\text{yield}} = 350 \, \text{MPa} \) [6]) for that condition which results in an allowable pressure loading of 2.8 MPa, exceeding our desired proof pressure by a factor of 9. Therefore, for the cryogenic tank, the end caps are the load limiting structure and finite element analysis conducted using SolidWorks indicates that no area on the cap has a safety factor less than 1.3 at 317 kPa (proof testing). The cap was meshed using triangular elements. Proof testing and maximum overpressure loads were applied to the inner surface of the cap while reaction forces were located on the outer surface of the cap coincident with bolt head locations.

Elastic buckling loads for the cryogenic cylinder and vacuum cylinder were analyzed. The cryogenic cylinder will operate under compressive loads when the tension rods are used to secure the end caps and crush the malleable Indium seal. In this case we assumed uniform longitudinal compression with unconstrained ends. The critical stress for this idealized case is given by:

\[
\sigma_{c1} = \frac{E}{\sqrt{3(1-v^2)}} \frac{t}{r}
\]
where $E$ is the modulus of elasticity, $t$ is the wall thickness, $r$ is the cylinder radius and $\nu$ is Poisson’s ratio. It has been noted [7] that empirical critical stress data approach the theoretical limit in eq. (1) to within 40 – 60%. Therefore, a more conservative value for critical longitudinal compressive stress is given by:

$$\sigma_{c,\text{emp}} \approx 0.3E \frac{t}{r}$$

(2)

For this system, we will torque the tension rods to generate approximately 1072 N tension each which results in a total clamping stress of $0.1\sigma_{c,\text{emp}}$. The cryogenic cylinder will also operate under vacuum conditions during helium leak testing, as will the vacuum cylinder during leak testing and normal operation. To estimate the critical pressure for this configuration, we assumed uniform lateral and longitudinal external pressure with closed ends held circular [7]. Critical pressure $p_c$ for each vacuum cylinder was estimated with:

$$p_c = \frac{E t^3}{12(\pi t^3)} \left\{ \frac{1}{n^2} \left[ \frac{n^2}{1+(n^2)} \right]^2 + \frac{n^2 t^2}{12r^2(1-\nu^2)} \left[ 1 + \left( \frac{2t}{n} \right)^2 \right]^2 \right\}$$

(3)

where $l$ is the cylinder length and $n$ is the number of lobes formed during buckling and is chosen to yield the lowest value of $p_c$. For both vessels, $n = 3$ and the critical pressure for the cryogenic and vacuum cylinder was 607 kPa and 338 kPa, respectively. The cylinders were determined to be sufficiently designed to operate at a maximum external pressure of 101 kPa during testing and operation.

The working pressure of the cryogenic tank will be maintained at 219 kPa using a pressure relief valve while a rupture disk will limit maximum overpressure to 232 kPa. Both pressure relief devices (not shown) are located on the vapor extraction tube leading to the heat exchanger (not shown). The vacuum port (Cryocomp V1025 seal-off valve) plug located on one end cap of the vacuum cylinder doubles as a pressure relief device for the vacuum space between the cylinders and is ejected at about 123 kPa. The two end caps on the cryogenic tank are held in place by 6 tension rods (Fig. 3) made from 6.35 mm diameter 6061-T6 aluminum tubing with 1.24 mm wall thickness. Threaded fittings made from 41L40 steel are bonded with Stycast 1266 epoxy and pinned in each end of the tube to accept 10-24 bolts. A 1.6 mm diameter Indium wire o-ring completes the seal between cap and cylinder at each end. The cryogenic tank is suspended within the vacuum tank with G10 rods at each end (Fig. 3) to reduce conduction heat loads. One rod is rigid while the other is comprised of two concentric, nested sleeves that contain a high compression spring (linear rate = 25 N/mm). The spring applies a force of ~ 67 N to maintain the relative position between the two cylinders while accommodating thermal contraction and expansion.
An insulating blanket made from MLI is wrapped around the cryogenic tank in the vacuum jacket to minimize radiation heat loads. The 1.91 cm annular space between the cryogenic and vacuum tank accommodates 30 alternating MLI layers. A packing density of 16 layers / cm was used and the multiple layers were secured as one unit with plastic price tag ties. To facilitate evacuation of the inter-layer spaces during pump down, the side and end seams of each layer were taped intermittently to allow gas molecule passage. A vacuum of approximately 10^{-5} Torr will be used to minimize gas molecule conduction between the cryogenic and vacuum tank walls and MLI layers. A vacuum valve seal-off operator (Cryocomp) is used to attach the vacuum cylinder to a roughing/turbo-molecular pump for evacuation.

The tank is filled (8.5 L capacity with 10% ullage space) using a bayonet that connects to a 0.95 cm nominal diameter tube. The tank will be filled with liquid hydrogen while located in the UAV at the flight test site to allow for atmospheric venting of hydrogen gas. Flow rate is dictated by feed tank pressure while a check valve (Generant part #CV-375B-T-.15-X) located in the vacuum space (Fig. 4) is used to prevent backflow after completion of filling operations. A cap (not shown) will be used to seal the bayonet opening. The check valve opens at 1.03 kPag and has a flow efficiency (C_v) of 3.9.

Vapor is extracted from the tank ullage space using a 0.64 cm nominal diameter tube after first passing through a phase separator (Taylor Wharton part #1193-8C83) to ensure vapor only transport. The fill and outlet tube sections in the vacuum space were lengthened to reduce conduction and positioned for natural stratification to reduce convection. Preliminary tests have indicated that the thermal contraction during fill has not compromised the copper face seal gaskets in the Swagelok VCR fittings and have remained leak free. Vapor leaving the tank flows through an insulated line before passing through a heat exchanger and pressure regulator that maintains 146 – 156 kPa pressure for the fuel cell. A baffle system comprised of an aluminum support tube and 3 baffle disks is suspended between the two end caps to minimize liquid hydrogen slosh which could initiate flight pitch instability.
Heat transfer due to radiation, conduction through the support rods and stainless steel fuel tubing, and residual gas molecule conduction between tank walls and MLI layers were analyzed to estimate liquid vaporization and mass transfer rates. A Crank-Nicolson (finite difference) numerical approach [8] was taken to model the vapor cooling effect on heat flux through the outlet tube into the liquid hydrogen cylinder. Vapor cooling of the fuel line tube was modeled with the outer vacuum cap as an extended surface with the outer most edge constrained to 300 K. A resistance network was used to model heat conduction through the liquid hydrogen fill tube and G10 supports. A layer-by-layer numerical analysis that included radiation, gas conduction, and separator conduction terms was implemented (following McIntosh [9]) to model heat flux through the MLI layers. All analyses were conducted using Engineering Equation Solver (EES) [10].

Heat transfer from conduction through the stainless steel tubes and G10 supports dominates the tank heat load (Table 2). During flight, H$_2$ vapor flow cools the outlet tube, removing 98% of the heat load through that source at cruise velocity and 99% during the climb phase, reducing the estimated total heat load into the tank to 1.15 W during cruise phase.

**TABLE 2.** Primary sources of heat loading (values for vapor cooling of extraction tube indicate cooling power).

<table>
<thead>
<tr>
<th>Heat leak type</th>
<th>Mechanism</th>
<th>Rate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS fill tube</td>
<td>conduction</td>
<td>0.71</td>
</tr>
<tr>
<td>SS vapor extraction tube</td>
<td>conduction</td>
<td>0.44</td>
</tr>
<tr>
<td>G10 supports</td>
<td>conduction</td>
<td>0.33</td>
</tr>
<tr>
<td>MLI + residual gas conduction</td>
<td>radiation + conduction</td>
<td>0.10</td>
</tr>
<tr>
<td>Vapor cooling of extraction tube (climb, cruise)</td>
<td>convection</td>
<td>-0.44, -0.43</td>
</tr>
</tbody>
</table>
The equivalent mass flow rate for a given throttle setting was determined from the volumetric fuel flow and power data provided for the Horizon H-1000 fuel cell used in the Genii UAV. A heat input of 9 W is required to vaporize sufficient hydrogen for a mass flow rate of 0.0206 g/s at take-off and climb with a throttle setting providing 979 W of fuel cell power. A heat input of 4.6 W is required to vaporize sufficient hydrogen for a mass flow rate of 0.0104 g/s for a cruise throttle setting providing 498 W of fuel cell power. We plan to provide supplementary heating with a ~10 W heater located in the tank.

**CONCLUSIONS & FUTURE WORK**

The design and fabrication of a light-weight, reconfigurable liquid hydrogen fuel tank for use on small (<25 kg) Unmanned Aerial Vehicles (UAV) has been completed. The use of Isogrid flanges allows for complete disassembly of the tank system for Technology Readiness Level (TRL) advancement of storage and fueling components. The total tank weight is 6.3 kg with an estimated parasitic heat load of 1.15 W during cruise.

Battery test flights of the Genii UAV began in mid-May and pressurized hydrogen tests will be completed before transitioning to liquid hydrogen later this fall. We plan to proof test the cryogenic vessel to 317 kPa prior to integrating the liquid hydrogen tank. The cryogenic vessel will be filled to 90% capacity with liquid nitrogen and allowed to vent at atmospheric pressure to test the Indium o-ring seal and threaded Swagelok fittings. The boil-off rate will be determined from mass measurements of the tank during venting after it has reached a steady state temperature. From the measured mass flow rate, the heat leak into the tank can be determined and compared with the numerical heat load predictions.

**ACKNOWLEDGMENTS**

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**REFERENCES**