Performance test of a 6 L liquid hydrogen fuel tank for unmanned aerial vehicles

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Abstract. A 6 L liquid hydrogen fuel tank has been designed, fabricated and tested to optimize boil-off rate and minimize weight for a 200 W light weight fuel cell in an unmanned aerial vehicle (UAV). The 200 W fuel cell required a maximum flow rate of 2.3 SLPM or less liquid hydrogen boil-off from the fuel tank. After looking at several different insulation schemes, the system was optimized as two concentric lightweight aluminum cylinders with high vacuum and multi-layer insulation in between. MLI thickness and support structures were designed to minimize the tank weight. For support, filling and feed gas to a fuel-cell, the system was designed with two G-10 CR tubes which connected the inner vessel to the outer shell. A secondary G10-CR support structure was also added to ensure stability and durability during a flight. After fabrication the fuel tank was filled with liquid hydrogen. A series of boil-off tests were performed in various operating conditions to confirm thermal performance of the fuel tank for a 200 W fuel cell.

1. Introduction

In the past several years there has been tremendous growth in the unmanned aerial vehicle (UAV) market. UAVs are being used throughout the world in many applications such as weather observations, surveying, agriculture, and reconnaissance. One challenge facing UAVs is the ability to perform for extended flight periods. Recent designs of UAVs have incorporated hydrogen as fuel of choice due to its light weight and high energy density [1-2]. Hydrogen, more specifically liquid hydrogen, has been used for many years by NASA as a rocket and shuttle fuel due to its superior properties and more recently has been looked into for UAV systems [3-5]. In 2012, Boeing’s liquid hydrogen powered HALE (high altitude long endurance) UAV, the Phantom Eye, completed its first autonomous flight. This vehicle is powered by two 150 hp internal combustion engines and was designed to maintain aloft for up to 4 days [6]. Other research is being conducted on smaller UAVs at the Naval Research Laboratory (NRL). The NRL introduced their Ion Tiger which was powered by a 550 W PEM fuel cell and recorded 26 hours of flight time for its first flight in 2009 using 5000 PSI gas hydrogen. In 2013, they upgraded their design from gaseous hydrogen to a 20 L liquid hydrogen tank which almost doubled the flight time at 48 hours [7]. Similarly another recent liquid hydrogen UAV system has also been developed by the Washington State University [8].

Recognizing the emerging domestic Korean and international hydrogen UAV market, in 2015 Hylium Industries Inc. started the development of a commercial liquid hydrogen and fuel cell power...
pack. This paper describes the first design iteration, fabrication and experimental results of this tank system coupled with a fuel cell.

2. Design

2.1. Initial design constraints

The tank system was initially designed to fit in the fuselage of a small UAV. The fuel tank volume allocation was a 500 mm long by 230 mm diameter cylindrical space horizontally located within the fuselage, and it had to contain at least 6 L (0.42 kg) of liquid hydrogen (LH$_2$). The fuel tank needed to be as light as possible but was planned to weigh a maximum of 3 kg for the first design iteration. The tank was planned to be paired with an available 200 W Horizon fuel cell model H-200 for the first set of tests [9]. From a calibration test, results presented in table 1, this fuel cell needed hydrogen supplied at a flow rate of 2.3 SLPM at a pressure of 1.5 bar absolute. From this flow rate and the latent heat of evaporation of hydrogen (455 kJ/kg), the maximum allowable heat leak to the inner tank was calculated at 1.52 W [10]. For a UAV using a continuous 200 W of power or a boil off rate of 2.3 SLPM, 6 L of hydrogen could theoretically supply 34.7 hours of power. Table 1 shows the power generated from the fuel cell, the necessary flow rate of hydrogen to generate that power, the time it would take to boil off 6 L of LH$_2$ at that consumption rate and finally the necessary heat needed to boil off the hydrogen from the inner vessel.

| Power generated from fuel cell (W) | Necessary H$_2$ flow rate to fuel cell (SLPM) | Est. boil-off time for 6 L of LH$_2$ (hr) | Necessary heat to achieve boil-off rate (W) |
|-----------------------------------|-----------------------------------------------|-------------------------------------------|-------------------------------------------|
| 50                                | 0.5                                           | 159.4                                     | 0.33                                      |
| 100                               | 1.0                                           | 79.7                                      | 0.66                                      |
| 150                               | 1.5                                           | 53.1                                      | 0.99                                      |
| 200                               | 2.3                                           | 34.7                                      | 1.52                                      |
| 250                               | 2.8                                           | 28.5                                      | 1.85                                      |

2.2. Tank design

To start the design, the inner vessel volume was set to 6.8 L; slightly larger than 6 L to allow for some dead volume in the top for liquid gas separation. From the set volume and a standard purchasable inner diameter dome size of 145 mm, the total length of the inner vessel was set at 440 mm. Material chosen for the tank was 6061-T6 aluminium due to its low density and low material cost. Next step was to tabulate heat leak from all sources starting with the insulating layer. The heat leak was calculated for various insulation schemes such as Aerogel blankets or beads, pearlite, and vacuum with multi-layer insulation (MLI) using published apparent thermal conductivity data [11-12]. Calculations revealed vacuum with MLI was the only insulation method which kept calculated heat leak and outer diameter size within the design constraints. Using Lydall’s data for their aluminum foil CRS wrap, heat leak through the MLI was under 0.18 W [12]. Therefore, in order to use this insulation scheme, the tank was designed as a cryogenic Dewar consisting of two concentric domed aluminum cylinders with vacuum and MLI in-between. At this point the dimensions of the outer shell could be set; the inner diameter was 195 mm also based on standard purchasable dome sizes and the length was 500 mm based on the maximum from the design constraints.
Before continuing the calculation of the conduction heat leak for the support structures, it was necessary to determine the approximate weight of the vessel so the support structures could be designed. The next step was to determine the thickness of the inner vessel and outer shell. Buckling analysis was conducted within a commercial 3D engineering CAD simulation software package to determine the necessary thickness of the inner vessel and outer shell. This analysis revealed that the required thickness with a safety factor of 1.5 for a 2 bar absolute inner tank and vacuum outer shell would be less than 1.5 mm. Welding thin aluminum less than 1.5 mm is inherently difficult, so to avoid these difficulties and other complications for the first fabrication the tank thickness was set at 1.5 mm. At 1.5 mm, just the inner vessel and outer shell were estimated to weigh approximately 2.1 kg total.

After determining the weight and size of the vessels the vent, filling, and support structures were designed and the conduction heat leak was approximated for each. To prevent contact of the inner vessel with the walls of the outer shell, the inner vessel was designed to be suspended by two axial support G10-CR pipes on either end of the cylinder; system diagram is shown in figure 1. On one side of the cylinder, there was an additional G10-CR connection to the outer shell which provided the filling point for the tank. This fill point was designed to attach to a vacuum transfer line with a bayonet connection. After detaching the fill line from filling port, the filling port can then capped. For the hydrogen exhaust or boil-off, the tank was designed with a 6 mm main exhaust line from the inner vessel. This line was wrapped in the middle of the layers of aluminum foil MLI which causes a vapor cooled shield effect due to the high conductivity of the aluminum. This 6 mm pipe was connected to the outer shell by another G10-CR pipe to limit conduction back down the vent. Expected heat leak from fill, vent and support structures was approximately 0.57 W which made the total calculated heat leak for this design from all sources ideally around 0.75 W. This heat leak performance, 0.75 W, was less than the calculated heat requirement to boil-off the hydrogen at 1.52 W for 200 W of power so additional heating would likely be required. From the first set of experiments presented in this paper, it was desired to know exact thermal performance of this system. The thermal performance would then dictate the size and necessity of a heater in later designs or if the insulation needed to be reduced. More practically, depending on the type of UAV system, it may not necessarily need 200 W of continuous power. During flight, increasing in altitude over one to two hours, conducting maneuvers or having a full payload, an UAV may use the maximum amount of available power. When it is just cruising or flying with a light payload, it will likely need a smaller amount of power. Therefore to avoid unnecessary fuel loss, it is better to reduce the boil-off to the normal or average steady state consumption rate of the aircraft and then add supplemental heating during the shorter periods of high power consumption.

![Figure 1. Simple schematic diagram of 6 L UAV LH₂ tank.](image-url)
3. Fabrication
After completing initial design, fabrication began on the tank. The first section fabricated was the inner vessel. The axial support structures and bayonet adapters were welded to the inner domes. The inner vessel was welded shut and the 6 mm vent line was welded in place, figure 2 (A). After welding the inner vessel, G10-CR pipes were threaded and glued with Loctite Stycast epoxy for the bayonet fill and exhaust lines. After sealing the G10-CR pipes and welding the inner vessel together, the vessel was helium leak tested at 7 bar and then thermal shock tested again at 7 bar with liquid nitrogen to verify leak tightness of the inner tank before continuing assembly.

After conducting the leak tests, the inner tank was wrapped with CRS wrap aluminum foil MLI from Lydall [12]. 10 layers of MLI were applied to the whole inner vessel then the 6 mm aluminum exhaust line was wrapped over it. The next 30 layers of MLI were added over the coiled tubing, figure 2 (B). The 6 mm tubing was in direct contact with the aluminum foil on both sides which created a vapor cooled radiation shield effect due to the high conductivity of the aluminum foil. After the MLI was wrapped over the inner tank, the outer shell was assembled and welded together over the inner vessel. Leak tightness of the outer shell was verified through vacuum and acetone testing. After finalizing the fabrication and testing, the vessel weighed in at 3.0 kg which met the initial target for the first design iteration. Figure 2 (C) shows the final assembly after a coat of paint.

4. Experiment

4.1. Instruments and Safety
After fabricating the tank, the experimental setup was plumbed together. Boil off from the tank would flow to a bypass during filling or flow to a 20 SLPM FMA 1600A mass flow meter (MFM) from Omega during the experiment. From the MFM the hydrogen would then go through the mass flow controller (MFC) provided by Horizon with their stack, or it would flow through a secondary bypass which prevented over pressurization. The secondary bypass consisted of an adjustable pressure regulator to maintain the 2 bar absolute pressure followed by a second FMA 1600A MFM to record any excess boil off not used by the fuel cell.

To provide an electrical load for fuel cell, a Prodigit 3311D 300 W load meter was attached to the system. Boil-off data was recorded with a Graphtec midi logger GL820. Experimental schematic diagram is shown in figure 3. To ensure vacuum level was constant and would not increase due to outgassing for the duration of the experiments, the tank was connected to Edwards EXT75DX turbo-molecular pump with a standard rotary vane backing pump. The vacuum level was measured with a Convectron vacuum gauge.

Safety was a high priority due to the use of liquid hydrogen. The experiments were conducted in a well-ventilated room under a large walk-in fume hood. During the installation of sensors and electrical equipment, care was taken to prevent spark sources and properly ground all equipment. Proper safety equipment was worn at all times when dealing with cryogenic liquids: face shields, insulated gloves, long pants, etc.
4.2. Preparations and transfer

To ensure good vacuum insulation, the system was prepared for liquid hydrogen by undergoing a helium purge and bake out process over the course of 24 hours. After baking the system was filled with liquid nitrogen via a vacuum insulated transfer line for a boil-off and final assembly test. This test was to evaluate if the tank had been assembled properly and determine if there were any unexpected problems. From the results presented in figure 4, it can be seen that the pseudo steady state boil-off rate was very high around 16 SLPM or heat leak of 65.5 W. It was also noted that there was moisture on the outside of the tank. Vacuum level was maintained approximately around 0.1 mTorr so this indicated vacuum level was good and there were no leaks. Since the vacuum level was good this data indicated that there was a thermal short occurring within the tank. To get a better idea of where the thermal short was occurring, it was decided to proceed with the filling of the LH$_2$ to see if a freezing

![Figure 3. Experimental flow and instrumentation diagram.](image)

![Figure 4. Liquid nitrogen boil off from preliminary test.](image)
pattern could be observed on the outside of the tank. In addition, it was also desired to test the operation of the fuel cell portion of the system as the hydrogen was boiling to test the operation of that portion of the system. The tank was refilled with a small amount of LN\textsubscript{2} to again cool the tank and transfer line. The transfer line and tank were then fully evacuated to remove any residual nitrogen.

4.3. Results preliminary LH\textsubscript{2}

After precooling and evacuating, the UAV tank was then placed on a generic scale and the valve on the liquefier was opened. 3 bar LH\textsubscript{2} flowed from the liquefier into the tank and it was filled with 6 L (0.42 kg) of LH\textsubscript{2}. After filing, the valves on the liquefier were closed, transfer line was detached and the UAV tank was capped thereby sealing the inlet. Data logging began immediately after sealing the system; boil-off data is presented in figure 5. The dips in the graph of figure 5 at the beginning were due to the adjusting of the regulator to slowly increase the pressure of the system to 2 bar absolute. After reaching 2 bar, the fuel cell was turned on and the load meter was set at 200 W. The boil-off from the hydrogen was very high exceeding the 20 SLPM of the mass flow meter. This result was expected based on the high boil off during the LN\textsubscript{2} experiment. The tank completely boiled off in 1.5 hr. In the graph there are spikes observed in the flow rate near the end of the experiment in figure 5; these spikes are due to the fuel cell mass flow controller valve opening and closing indicating everything was working properly. After starting to fill the tank for this experiment, it was noted ice quickly formed on the whole outer surface, which was measured at around 250 K. After 1.5 hr when the hydrogen was boiled off, the ice on the outer surface began to thaw. The thawing pattern indicated an unexpected cold region at the bottom of the vent side of the tank. This was a strong indication that the inner vessel was not axially aligned inside; the G10-CR support structure was not attached properly to the outer dome. The MLI was pressed against the outer wall creating a thermal short in the region. Moving forward in this system’s development, this issue will need to be fixed or addressed in the next design iteration.

![Figure 5. Liquid hydrogen boil off from preliminary test.](image-url)
A 6 L LH$_2$ vessel for UAVs was designed, fabricated and tested. Preliminary LN$_2$ and LH$_2$ tests revealed there was a thermal short which needs to be repaired. Operationally attaching the LH$_2$ tank to the fuel cell during the LH$_2$ preliminary test went relatively smoothly. The fuel cell and load generator operated correctly while feeding off the boil off from the tank. Moving forward, planned design changes include thinner aluminum tanks to reduce the weight. Changing the tank material to stainless steel will also be explored as possible option to thin the vessel and reduce the weight. Finally, the support design will be reevaluated and redesigned to ensure easier assembly and avoid thermal shorting in future fabrications.

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