

Design of a Helium Vapor Shroud for Liquid Hydrogen Fueling of an Unmanned Aerial Vehicle (UAV)

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Abstract. Filling a vehicular liquid hydrogen fuel tank presents the potential for flammable mixtures due to oxygen concentration from liquid air condensation. Current liquid hydrogen tank designs utilize insulating paradigms such as aerogel/fiberglass materials, vacuum jackets, or inert gas purge systems to keep the outer surface from reaching the condensation temperature of air. This work examines the heat transfer at the refuelling connection of the tank to identify potential areas of condensation, as well as the surface temperature gradient. A shrouded inert gas purge was designed to minimize vehicle weight and refuelling time. The design of a shrouded inert gas purge system is presented to displace air preventing air condensation. The design investigates 3D printed materials for an inert gas shroud, as well as low-temperature sealing designs. Shroud designs and temperature profiles were measured and tested by running liquid nitrogen through the filling manifold. Materials for the inert gas shroud are discussed and experimental results are compared to analytical model predictions. Suggestions for future design improvements are made.

1. Introduction

Hydrogen fuel cell powered Unmanned Aerial Vehicles (UAVs) have the potential to be a disruptive technology for the current UAV market once storage and fueling issues are overcome. The density of liquid hydrogen is very compelling for long-endurance UAV applications. In recent years, 3D printed tank technologies have emerged that significantly increase the robustness, while reducing costs, of liquid hydrogen tanks (Adam, 2017). However, significant system design remains before field-implementation.

Liquid hydrogen refueling systems must account for fluid temperatures far below the condensation temperature of ambient air. Maintaining the temperatures of exposed fueling components above 78.9 Kelvin will prevent the condensation of air on refueling components.

In this work, we design a system for mitigating the air condensation hazard associated with refueling small UAVs. A preliminary design matrix is constructed that weighs multiple design factors. A gas purge system was selected as the most feasible design paradigm given the low weight and rapid refueling requirements of the UAV. Factors affecting material design and sealing are discussed. A design prototype is constructed and tested with liquid nitrogen flows. The experimental temperature measurements are compared to an analytical heat transfer model.



2. Design

An initial scoping interview was held and the primary factors most affecting the design were determined to be: 1. Capital costs, 2. Recurring costs, 3. Encumbered weight on the aircraft, 4. Simplicity of use, and 5. Safety reliability. Three design paradigms are considered for mitigating air condensation: 1. inert gas shielding, 2. Cryogel® insulation, and 3. Vacuum-jacketed insulation. These design factors and paradigms are compared in the following design matrix and binned (low, medium, high).

Table 1. Design matrix for mitigating air condensation.

<u>(Low = 1, Medium = 3, High = 5)</u>	Goal	Inert Gas Shielding	Cryogel® Insulation	Vacuum Insulated Shell
A. Capital Costs	Minimize	Low	Medium	High
B. Recurring Costs	Minimize	Medium	Low	Low
C. Aircraft Weight	Minimize	Low	Medium	High
D. Usability/Simplicity	Maximize	Medium	Low	Medium
E. Safety/Reliability	Maximize	High	Medium	Medium
<u>Total (goal is minimum)</u>	(A+B+C-D-E)	-3	3	5

Cryogel® insulation is a commonly used aerogel/fiberglass type insulation. It will prevent condensation with thicknesses of 5 mm. At a conductivity of 19 mW/m*K at 77 Kelvin, it has one of the lowest thermal conductivities of any insulation, however Cryogel® produces substantial amounts of aerogel dust during installation and removal of the insulation. This requires careful handling. Cryogel® adds additional weight to the system, however, Cryogel® requires no maintenance once attached and the only reduction in system performance is due a minor increase in weight.

Vacuum insulation is a more complex option due to the need for a pump to evacuate the cover placed over the manifold. This design would be similar to a suction cup, however it requires a pass-through system for the fluid lines. This requires more extensive redesign of the system and increased refueling time. For these reasons, complexity of the system is increased and is not considered for use.

Inert gas shielding was selected for being a simple solution to prevent condensation on the refueling flange. Gas shielding does not require additional weight as a shroud is easily removed. Helium and Nitrogen are considered for shielding gasses. Helium is required on site to purge the interior of the LH2 tank prior to fueling and can also be used as an inert gas shield. Nitrogen is considered due to the low cost of nitrogen gas. Although nitrogen gas is roughly one eighth of the price of helium gas it was determined that helium was the best choice for this system as nitrogen gas can condense on the surface of a liquid hydrogen tank. This condensation results in higher heat transfer, equivalent to 10 to 100 times more heat going into the liquid hydrogen causing more hydrogen boil off. Helium will not condense on the surface due to its saturation temperature of 4.2 Kelvin at 1 atmosphere. The need for a helium purge onsite would necessitate managing nitrogen and helium separately, if nitrogen were selected.

The method of manufacturing influences the production cost, strength and dimensional quality. The potential production methods include fused deposition manufacturing (FDM) 3D printing, conventional metal machining and composite construction. Composite materials allow for a shroud with a small coefficient of thermal expansion. Minimizing the coefficient of thermal expansion is ideal to prevent thermal stress. The manufacturing constraints associated with composite use prevent complex shapes and increase manufacturing time due to the need to produce a mold for each iteration and resin curing time. Conventionally milling from aluminum results in a sturdy design with a relatively fast production time for each iteration of the shroud. The material cost associated with conventional milling is also greater than the comparable 3D printing method.

FDM is selected to produce inexpensive vapor shroud prototypes and compatible printers are in-house. Polylactic Acid (PLA) is selected for the initial prototype due to its ease of printing and low cost. Thermoplastic polyurethane (TPU) Flexible Graphene filament is selected for the final design to achieve the required strength and electrical conductivity of the shroud. Grounding the shroud is required to minimize sparking during refueling. Shroud prototypes are test fit after each design change to determine if any geometric issues between the shroud and refueling flange occurred due to changes made in the CAD model.

Two design paradigms for sealing the shroud to the tank body are considered: 1. a friction fit seal where the sealing material is compressed when the shroud is fitted, and 2. a mechanical clamping system in which the clamping force on the sealing material is applied externally. The mechanical clamping system considered utilized a Teflon surface on the interior of the vapor shroud that would contact the refueling flange when an external clamp is tightened. A mechanical clamp would require more moving parts and because of this an increased risk of failure while the system is in use. For this reason, the mechanical clamping method was rejected. The sealing materials under consideration include silicone rubber, Teflon, and indium seals. Silicone rubber sealing utilizes a flexible strip attached to the vapor shroud that provides a barrier between the shroud and refueling flange to prevent gas loss. It has low sealing force, which makes its ease of use much better than Teflon. There are also concerns that higher sealing pressure with Teflon would result in significant fatigue in the shroud structure. Due to its simplicity and reliability, the friction seal option with a silicone rubber seal was selected.

3. Testing

The prototype shroud is assembled on a pre-existing tank flange and liquid nitrogen is flowed through the refueling connections to simulate a liquid hydrogen flow. Both the liquid inlet line and flange are stainless steel. They are mounted to an aluminum holding fixture with Cryogel® insulation. The flange configuration remains unchanged with addition of the vapor shroud. The left panel of Figure 1 shows liquid nitrogen flowing in from the top of the image. Through an uninsulated tube (now icing in the image), then flows into the tank. As the tank is filled ice buildup continues throughout the flange, as shown in the central panel of the figure. The condensation of liquid air is more difficult to observe. In the right panel of the figure, the vapor shroud covering the refueling flange is shown with no visible icing or condensation immediately after a 15-minute fill with liquid nitrogen.

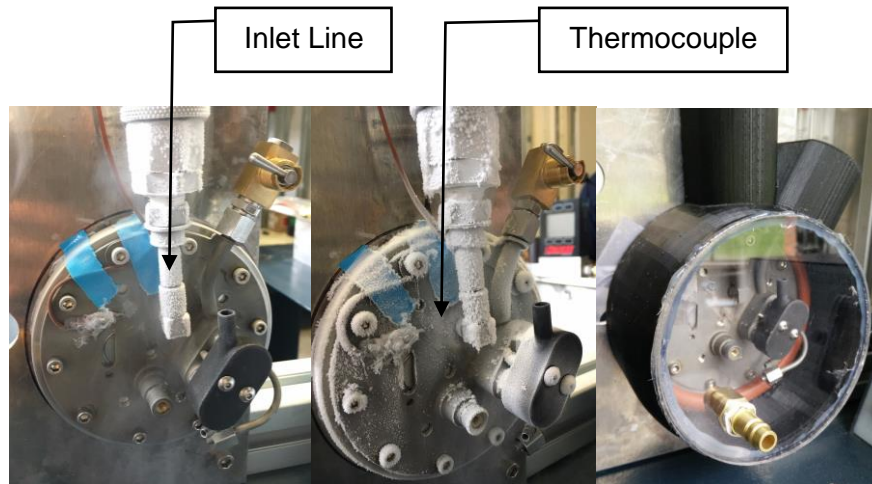


Figure 1. (Left Panel) Unshielded refueling flange at the beginning of LN2 flow. (Center Panel) Unshielded refueling flange after 5 minutes of LN2 flow. (Right Panel) Shielded refueling flange after 15 minutes of LN2 flow.

Purge tests were conducted at 20, 40, and 80 LPM of helium flow into the top of the shroud. At 80 LPM no condensate (water or air) was observable. 40 LPM of nitrogen was also tested as a lower cost alternative and showed the same qualitative visual results as 80 LPM of helium.

Temperature is measured on the flange by a Type K thermocouple on the flat surface of the plate 11.43 mm from where the tubing meets the flat plate flange (shown in Figure 1). As can be seen in Figure 2, the flange temperature approaches 170 K in both the nitrogen and helium purges. While this observation verified the capability of the shroud to mitigate air condensation, a model was constructed to provide quick reference should additional alterations to the shroud be required.

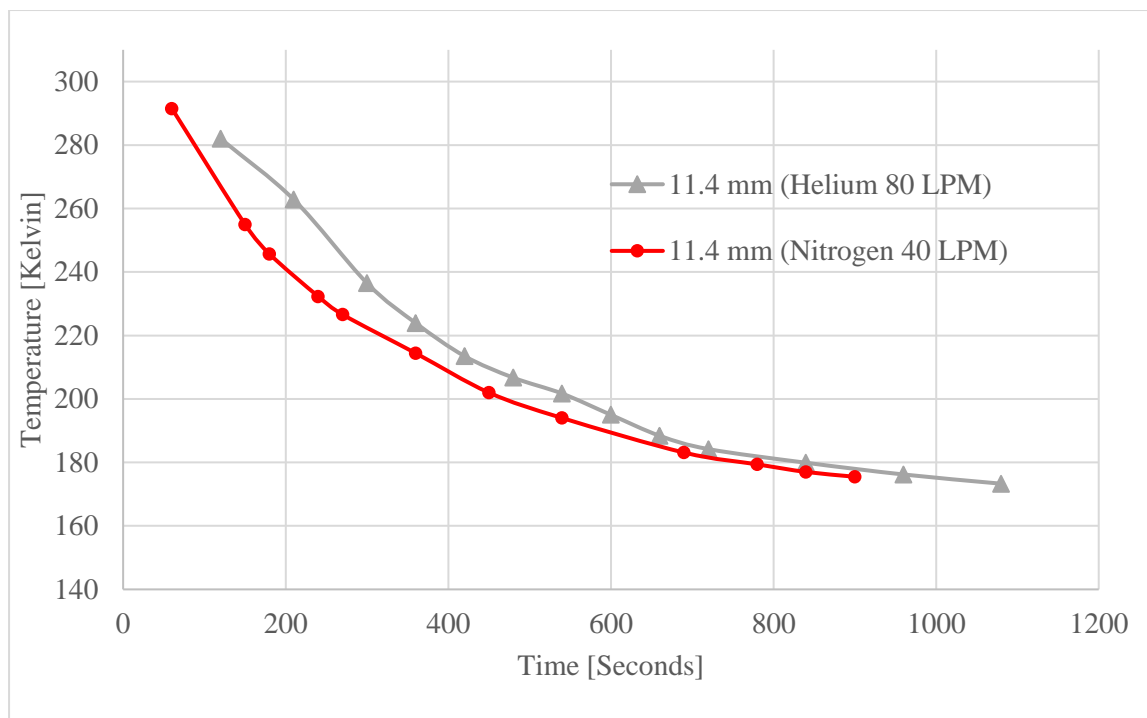


Figure 2. Liquid Nitrogen Cooldown simulated tank fill. Lines show the two different purge gasses used when purging the area around the uninsulated surfaces.

4. EES Model/Analysis

To estimate the thermal behavior of the flange, a finite difference model was developed using Engineering Equation Solver (EES) (F-Chart). The model assumes the flange follows the extended surface approximation with a disk with conduction occurring radially in the disk as well as convection vertically with gas flowing over it. The code used a one-dimensional analysis that included the following assumptions:

- the inner wall, at $R = 3.5$ mm is the inner annulus of the disk being modeled. This represents the outer wall of the tubing carrying the liquid nitrogen/hydrogen. The outer radius being the outer ring of the flange. Both the temperature data collected and the model use transient analysis for validation.
- Temperature dependent material properties of stainless steel (Ho, 1977)
- The bottom of the flange was assumed adiabatic due to very high thermal resistance of the insulation layer beneath it.
- The top accounts for the heat flux from the helium flowing over the top of it.
- The inner wall where liquid flows is assumed to be constant temperature due to the high heat transfer rates that occur when boiling the fluid

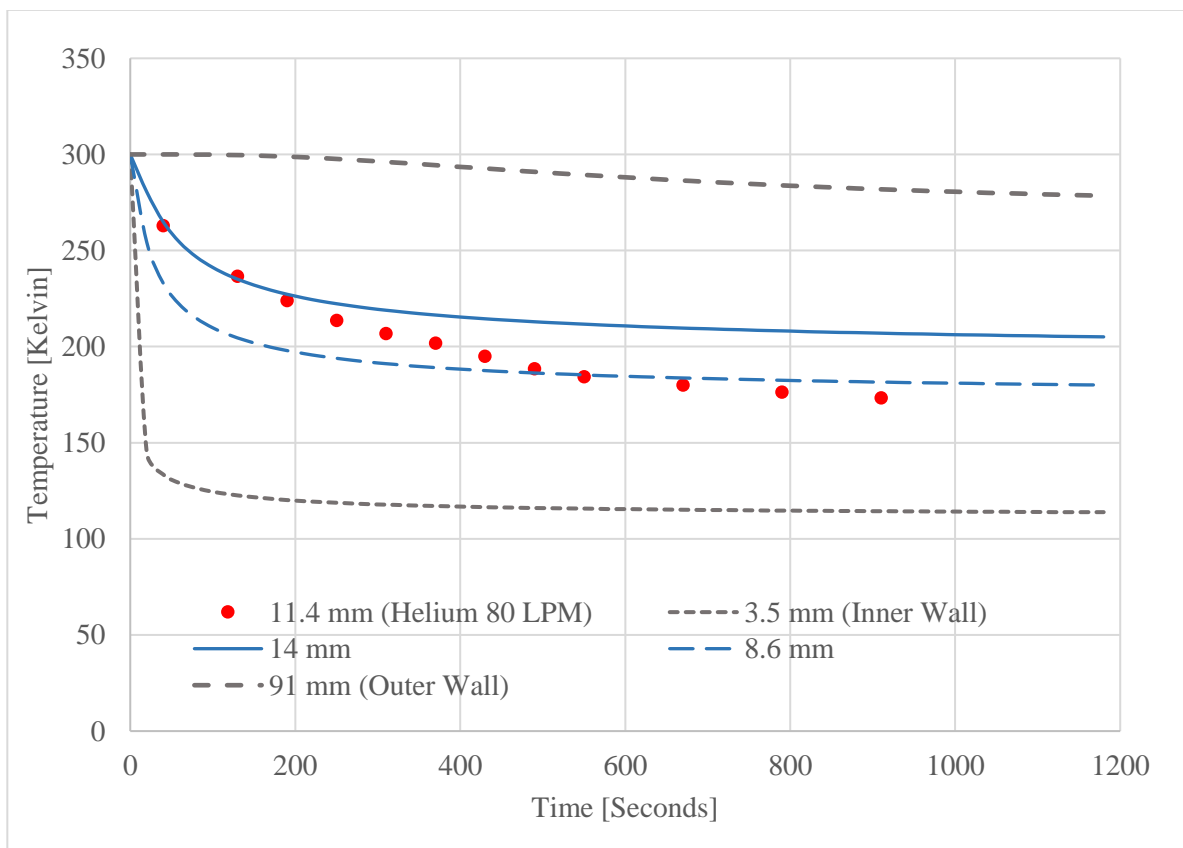


Figure 3. Model Comparison with liquid nitrogen and helium purge gas flow data. Dotted data points are generated from Figure 2. Lines ,dashed and solid, correlate to numerical model.

Given these assumptions, the simplified 1 dimensional model has a deviation from the experimental results at the measured 11.43 mm from the inner wall. These can be accounted for in the non-uniformity of the refueling plate, as well as an aluminum back plate that was only included to hold the flange in place. There is a longer time-delay in cooling due to the added mass from the simulated test. For this reason, the model is expected to be more representative of realistic tests.

The data collected with Liquid Nitrogen (LN2) and helium flowing through the shroud is compared to the numerical model. Figure 4 shows the steady state temperature distribution calculated from this model, flowing both liquid nitrogen and liquid hydrogen into the tank, with a helium purge gas for each.

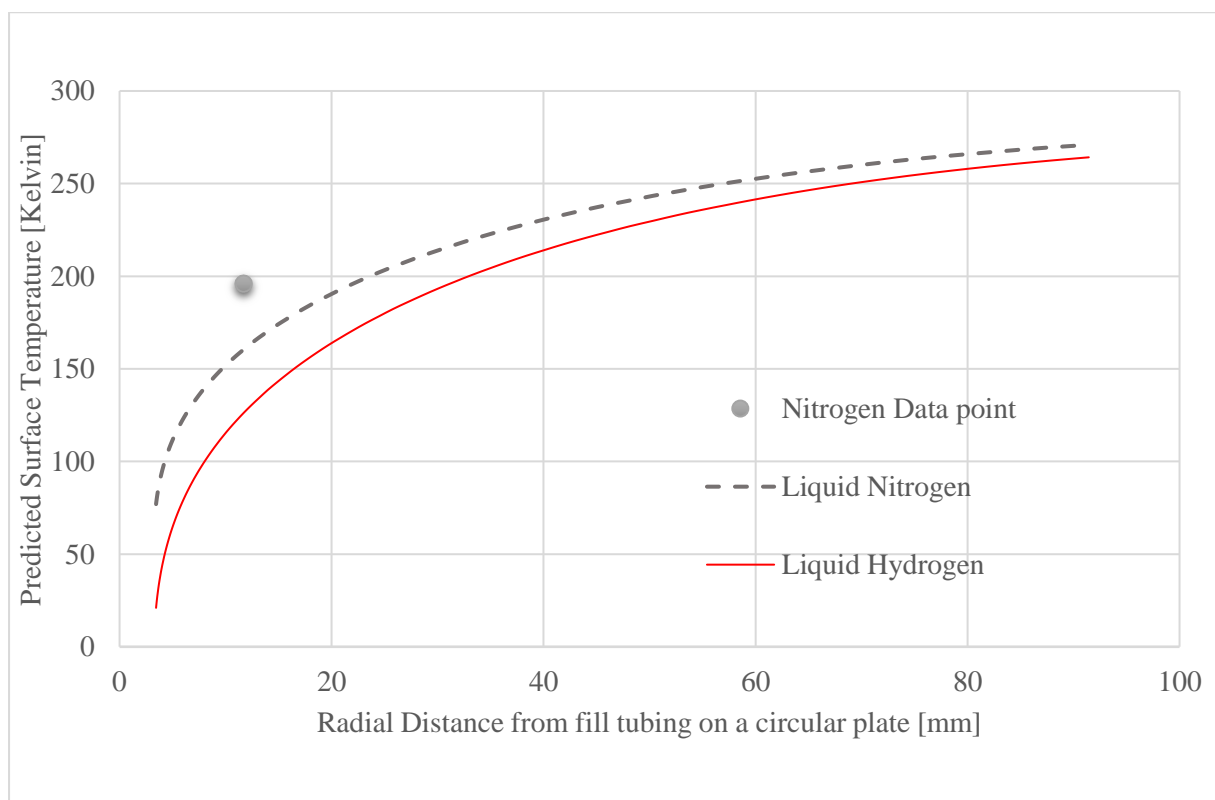


Figure 4. Steady State Temperature Distribution with Different Fluids Flowing into the Tank. Derived from numerical model

5. Conclusion and future improvements

The design and initial performance of a prototype liquid hydrogen UAV refueling shroud was presented. Visual inspection and temperature measurements during liquid nitrogen fills indicate the shroud design is successful at mitigating air condensation. The shroud developed allows for improved fueling without additional weight to the vehicle. By incorporating ESD prevention as well as eliminating condensation on the surface, we can refuel with liquid hydrogen and mitigate ignition risks. Additional testing of the shroud to survive repeated thermal cycling and drops in the field are recommended.

References

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Acknowledgements

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