Computational Fluid Dynamics Model of a 3D Printed Liquid Hydrogen Tank with Vapor Cooled Shielding for Use in Unmanned Aerial Vehicles

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HYPER: Hydrogen Properties for Energy Research

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MOTIVATION

Unmanned aerial systems (UASs) perform critical tasks such as observation and reconnaissance where use of manned aircraft is cost prohibitive or dangerous. While aircraft guidance and remote sensing technology have rapidly developed, propulsion systems for small scale UASs have not dramatically changed, typically relying on internal combustion engine (ICE) technology. ICE propulsion systems are noisy and produce significant vibrational loads on the airframe and payload while presenting mechanical wear issues. Electrical propulsion systems using battery power are quiet and impart minimal vibrational loads to the aircraft, but are limited to flight times typically less than one hour. Fuel cell powered propulsion systems using hydrogen are a compelling alternative that combine the quiet, reliable attributes of electrical propulsion with flight times that approach that of gasoline powered UASs.

GOAL

UAS manufacturers are currently developing fuel cell powered variants of their gas powered aircraft. Fueling options include compressed gas and cryogenic liquid hydrogen. A liquid hydrogen storage system was determined to provide higher energy density (MJ/m^3), specific energy (MJ/kg) and gravimetric capacity (H_2 wt%) than a high pressure (350 or 700 bar) gas system. Our goal is to design, build, and validate a liquid hydrogen storage system that integrates the heat exchanger into the tank wall to minimize system mass and volume while reducing heat flux into the tank. This research presents the computational fluid dynamics and thermal modeling of

TANK DESIGN

- Cooling in vapor channels enhanced by para-orthohydrogen conversion
- 3D printed shells allow for complex heat exchanger flow geometry
- Copper electroplating on shells creates hydrogen permeation barrier
- Integrated temperature sensors and heater provide mass flow control
- Insulation material minimized by relying on vapor cooling
- CryoGel (aero gel derivative) used for remainder of thermal barrier
- Insulating cavities filled with CryoGel are evacuated

COMPUTATIONAL FLUID DYNAMICS MODEL

A 2D axisymmetric thermal-fluids model was developed in COMSOL Multiphysics to evaluate the optimal configuration of counter-flow gas passages and insulation cavities. Heat flux into the tank was tuned by varying the thickness of vapor ducts and insulation cavities until the required mass flow rate was achieved. The outer vapor duct was situated along the outer shell to ensure the hydrogen would reach ambient temperature before leaving the tank for the fuel cell, eliminating the need for a separate heat exchanger.

Convective Heat Transfer

External — The tank, while enclosed in the airframe, may be subjected to forced convection heat transfer due to a lack of air tight seals used in hatches and other hull penetrations. A free-stream velocity of 5 m/s is assumed to flow past the cylinder in the axial direction. The tank was modeled as a sphere due to the 1:1 aspect ratio of diameter to length.

Internal — Two modes of liquid hydrogen convective heat transfer are considered during operation. A transient analysis simulating tank fill and cool down is conducted that uses an integrated average of the film and nucleate boiling regimes (700 W/m^2-K). A steady state analysis is conducted assuming natural convection for the subcooled liquid condition where turbulent flow is indicated by a Rayleigh number of 1.2E9-1.2E10 for the tank geometry.

Radiation

Radiation across the vapor duct walls was neglected due to the small average temperature between the opposing walls that resulted in an approximate radiation heat transfer coefficient of 0.6 W/m^2-K.

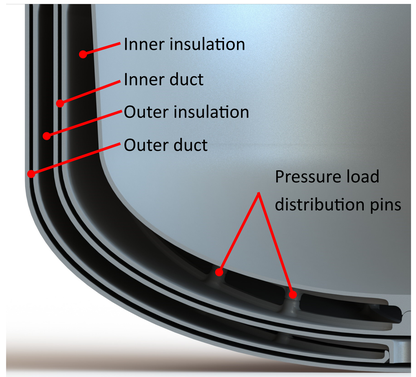

Figure 1. Cross section of tank illustrates vapor passages and inert gas fill / insulated layers.

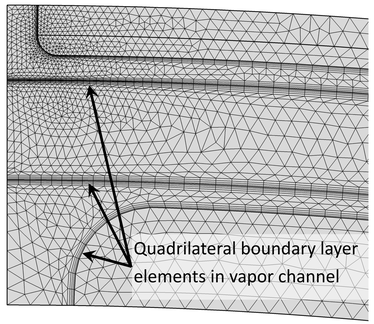

Figure 3. 26921 triangular elements used for fluids and solids. 12500 quadrilateral elements used (4 elements deep) for fluid boundary layers.

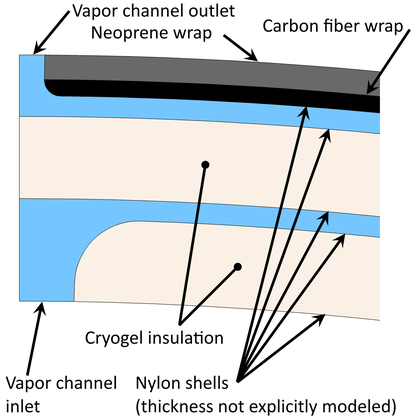

Figure 2. Close-up of simplified CFD model cross-section with material composition.

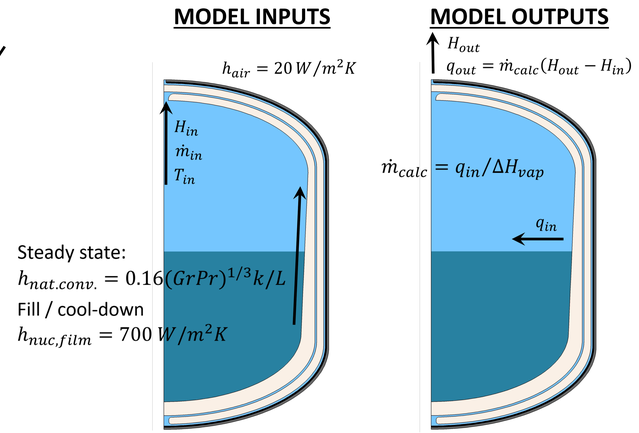

Figure 4. Liquid nitrogen fill level shown, liquid hydrogen modeled with full tank. Integrated average film boiling and nucleate heat transfer was used during cool down phase, while natural convection heat transfer was used during steady state for liquid hydrogen.

LIQUID HYDROGEN MODELED PERFORMANCE

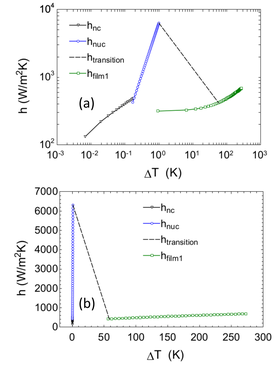

Figure 5. Heat transfer coefficient for hydrogen boiling curve. (a) log (b) linear plot. ΔT = wall temp-liquid film temp.

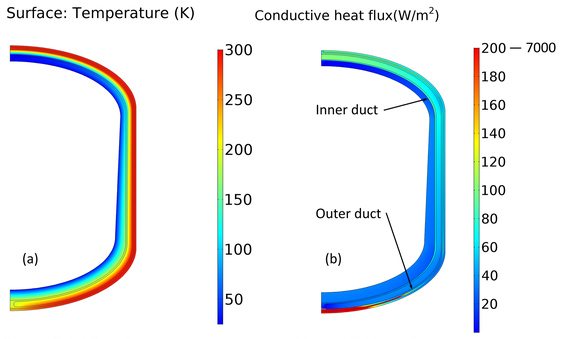

Figure 6. (a) Steady state temperature profile and (b) heat flux.

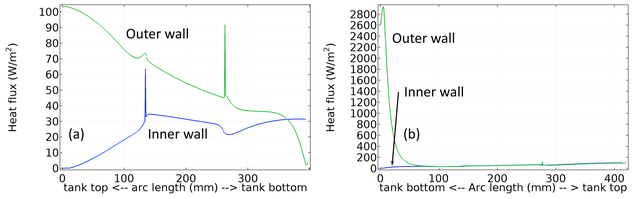

Figure 7. Steady state heat flux across inner and outer wall of a) inner duct and b) outer duct. Sharp spikes in plot (a) are due to modeling artifacts at edge junctions. High heat flux across outer wall in the outer duct (b) due to separation of 200K gas and 293K exterior by 3.8 mm thick section of nylon shell, carbon fiber shell, and neoprene sleeve.

RESULTS

- Para-orthohydrogen conversion in vapor duct provides 5 W additional cooling power
- Vapor jacket results in 44 W cooling power
- 5.2 W heat load into liquid
- Results assume 0.01 torr pressure in insulation layers

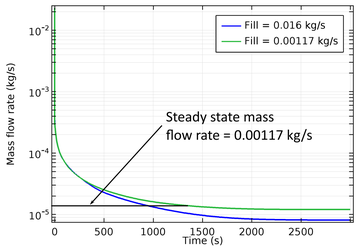

Figure 8. Cool down time from room temperature to steady state operating temperature was complete when the calculated mass flow rate reached parity with the cruise mass flow rate. The higher mass flow rate cooled the tank in 18 minutes. The lower mass flow rate, representative of a typical fill, cooled the tank in 29 minutes.

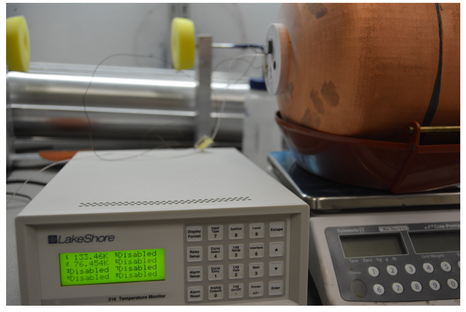

Figure 9. Internal gas and liquid temperature of nitrogen during mass boil-off tests.

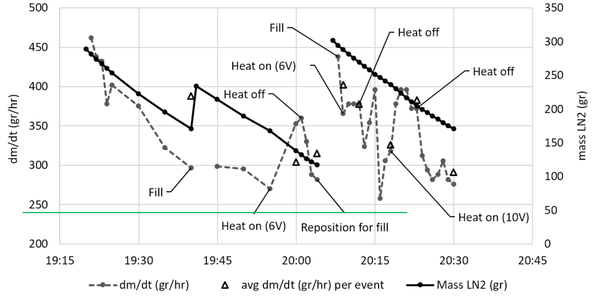

Figure 10. Mass flow rate (dashed line), liquid nitrogen mass remaining (solid lines) and average mass flow rate between fill, heater test, and tank repositioning events. Modeled steady state mass flow rate = 245 gr/hr (green line).

MODELED & EMPIRICAL NITROGEN PERFORMANCE

- The lowest measured mass flow rate exceeded the modeled mass flow rate by 4%
- A longer cooldown period may be required to achieve a more stable steady state mass boil-off rate
- Future mass boil-off tests will be conducted with full tank of liquid nitrogen and liquid hydrogen

VAPOR COOLED LIQUID HYDROGEN TANK SPECIFICTIONS