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THERMAL MODEL OF A ZERO BOIL OFF SYSTEM FOR THE NUCLEAR THERMAL PROPULSION SYSTEM

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NASA is currently developing an updated concept for a nuclear thermal propulsion (NTP) system. To enable this concept, efficient thermal insulation and cryocooler heat exchanger systems are required to eliminate boil-off of propellant. This paper presents the results of a thermal model used to assess the feasibility of using active cooling with a tube-on-tank heat exchanger configuration for the inline tank of the NTP system. Results show that: (1) cryocooler working fluid temperature and mass flow rate can be adjusted to achieve zero boil off (ZBO) with broad area cooling, (2) over-sizing the cryocooler lift directly translates into a reduction in tank pressure, and (3) broad area cooling may still maintain ZBO despite the reduced heat transfer between tank wall and propellant that is expected in reduced gravity.

I. INTRODUCTION

The nuclear thermal propulsion (NTP) project is developing an updated vehicle design (structural and thermal), concept of operations, and supporting trade studies and analyses to mature the NTP storage and transfer system. One of the supporting analyses is to determine the feasibility of using a cryocooler heat exchanger along with broad area cooling to maintain zero boil off (ZBO) of the liquid hydrogen propellant. ZBO can be achieved through a combination of passive cooling via multi-layer insulation (MLI) as well as active cooling via cryocooler heat exchangers. The cooling gas in the heat exchangers is helium, which is the working gas in the cryocooler system--a reverse turbo-Brayton cycle cryocooler. NASA is currently advancing the technology of this Brayton cycle cryocooler with a 20 W at 20 K development to enable such systems as NTP[1].

Figure 1 shows the current mission timeline for assembling the NTP vehicle. As shown, the system requires six Space Launch System (SLS) class launches for the deep space habitat, three inline stages, core stage, and crew habitat into Lunar Distant High Earth Orbit Components of the vehicle are then assembled in a near-rectilinear halo orbit (NRHO), which results in an insulation background temperature of 106.5 K, which drastically reduces the radiative heat load into the propellant relative to a traditional low Earth orbit. However, given the size of the tanks and that structural heating can be significant, it is still necessary to determine if a tube-on-tank system can maintain ZBO. Furthermore, studies have shown that heat transfer between fluid and solid wall (e.g. Ref. 2) is reduced in reduced gravity due to the lack of buoyancy force, which may affect the response and efficiency of a tube-on-tank heat exchanger. Therefore, the purpose of this paper is to develop a thermal model of the NTP propellant tank with tube-on-tank active cooling, determine a zero boil off point solution, and determine the response of the system to reduced heat transfer that is anticipated in reduced gravity.

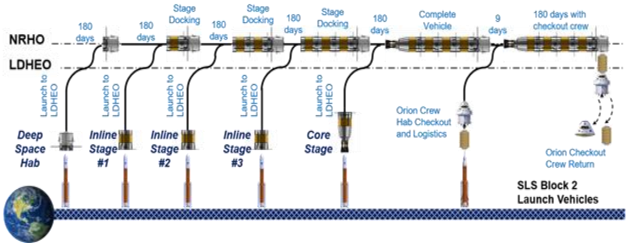

Figure 1. NTP mission timeline for vehicle assembly in NRHO.

II. THERMAL MODEL

A transient Thermal model using Thermal Desktop (TD)/Sinda-Fluint was constructed for the stainless steel inline stage of the NTP system shown in Fig. 2. The TD model of the tank with cooling tubes is shown in Fig. 3. Conduction, radiation, and orbital heating are all included in the model. The tank diameter is 7.1 m with end-to-end tank height of 8 m. The forward and aft ends of the tank are connected to a truss via composite struts. Specific structural details are available in Ref 3. The fluid inside the tank is modeled using a twin lump to capture heat transfer between the fluid and tank wall and phase change. Heat transfer between the gaseous helium in the tubes on the tank to the tank wall is also modeled. As shown in Fig. 3, six pairs (twelve tubes total) of evenly spaced aluminum supply and return tubes are used to circulate gaseous helium from the cryocooler (not shown). A single 20 K stage cryocooler with 40 layers of traditional MLI was used in the study.

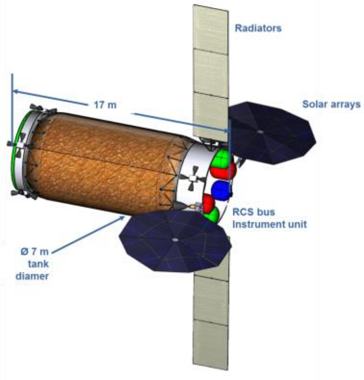

Figure 2. Inline LH_2 NTP storage tank with insulation and support structure attached.

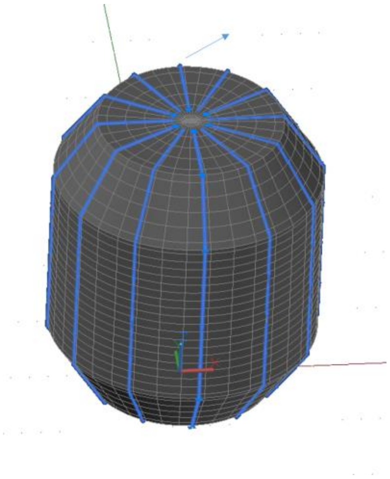

Figure 3. Thermal Desktop tube-on-tank nodal model.

Initial conditions were as follows: the tank was filled with 70% liquid hydrogen, 30% vapor. The initial temperature of the liquid was at 24.2 K, at a saturation pressure of 40 psia, while the initial vapor was assumed to be 34 K to include an initial liquid/vapor stratification. This assumed 10 K stratification in the LH_2 ullage temperature was common in a series of LH_2 pressurization tests at K-Site in the 1990's. The initial temperature of the wall was at 24 K. The environmental sink temperature was taken as 106.5 K. Initial modeling and sizing of a single stage cryocooler system using the Cryogenic Analysis Tool (CAT) from Ref. 3 indicated that the cryocooler needed to lift approximately 114 W of heat from the system, 97 W from the tank and 17 W from the gaseous helium supply and return lines to the cryocooler. Therefore, an e* value of 0.0661 in TD was thus used to match the 97 W heat leak from the CAT cryocooler sizing.

III. RESULTS AND DISCUSSION

III.A. Effect of Cryocooler Power Modulation in 1-g

To remove the 97 W of tank heat leak, assuming a 1-g environment, the cryocooler input power is 6000 W and the helium working gas flow rate is 0.1468 kg/s. At this set point, the nominal LH_2 saturation condition of 23.86 K and 37.2 psi is achieved within about 10 hours, as shown in Fig. 4. The initial drop in temperature is due to the application of cooling to the tank wall, quickly dropping its temperature along with that of the ullage and liquid. After the initial temperature decrease, the liquid settles out at a constant temperature over time. The first parametric performed is the system response to the application of cryocooler power, realized through changing the helium flowrate. Ref. 4 describes the documented ZBO test results that show the cryogen behaved like a de-stratified or homogenous fluid in response to varying cryocooler set points; this homogenous behavior was assumed herein. The tank pressure response to increased and decreased cryocooler mass flow rates is shown in Figs. 5 and 6. As indicated, the tank pressure directly responds to changes in cryocooler mass flowrate and the rate of these changes increase and decrease similarly. Increasing flowrate decreases tank pressure, enabling a straightforward control scheme and an effective power storage useful for eclipses or other unknown thermal events. This offers a reduction in power storage requirements and more straightforward flight operations scenarios.

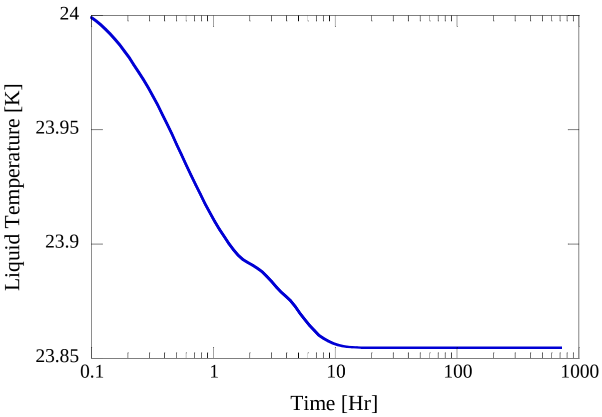

Figure 4. LH_2 saturated temperature plotted at ZBO condition.

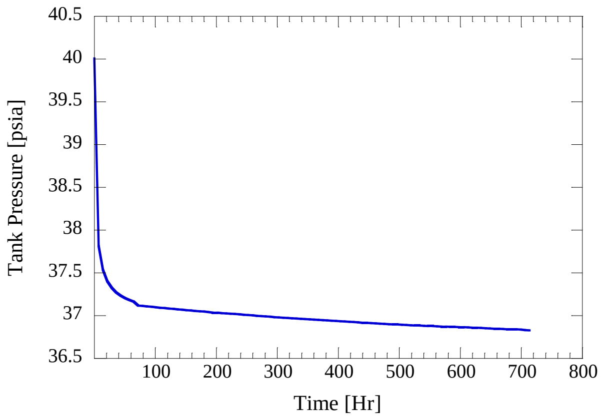

Figure 5. LH$_2$ tank pressure plotted with 5% increased cryocooler lift.

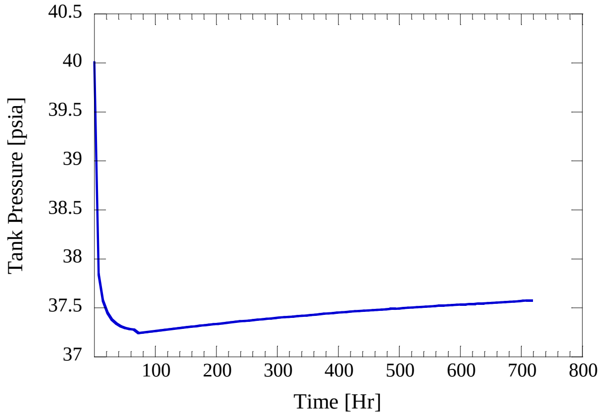

Figure 6. LH$_2$ tank pressure plotted with 5% decreased heat removal rate.

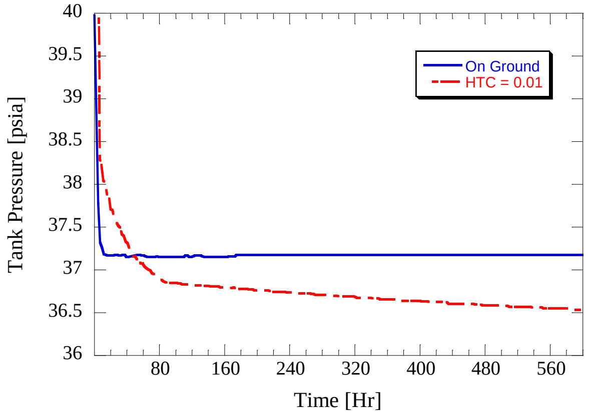

Figure 7. Tank pressure response comparison of 1-g and assumed reduced-g HTC.

III.B. Effect of Reduced Heat Transfer Coefficient

After orbital insertion, the thrusting ends and a microgravity environment ensues that potentially alters the liquid hydrogen's response to the ZBO system. Previous reduced gravity flight experiments have found reduced heat transfer coefficients compared to ground values for storable fluids (see Refs. 5-11 for example) as well as cryogens[2]. While it is difficult to estimate the actual heat transfer coefficient for liquid hydrogen in micro-gravity, it is straightforward to look at reduced Earth gravity (1-g) coefficients. This study considered 1-g heat transfer coefficients (HTC's) and 1% of that, or 0.01*1-g HTC, which represents a near-100% conduction limit. The results are shown in Fig. 7. As in the 1-g case, the initial application of tank wall cooling causes the tank pressure to drop. The reduced HTC takes about 80 hours to respond to the tank's broad area cooling system after launch, in comparison to 10 hours for the 1-g case. Following the 80 hour period, the low HTC tank pressure continues to drop, however, it is expected to increase and settle out at 37.2 psi over time, in response to the cryocooler set point and the balance of heat the ZBO system creates. Given that the liquid hydrogen is transferring much less heat than in 1-g and that the cryocooler is still removing heat at a steady rate, the system responds by dropping the tank wall temperature, causing the ullage pressure to drop. This is indicated in the comparison of temperatures for the two cases in Figs. 8 and 9. Much of the tank surface in Fig. 8 is at 23.87 K, while the greatest portion of the low HTC tank wall temperature is less, between 23.83 and 23.6 9 K.

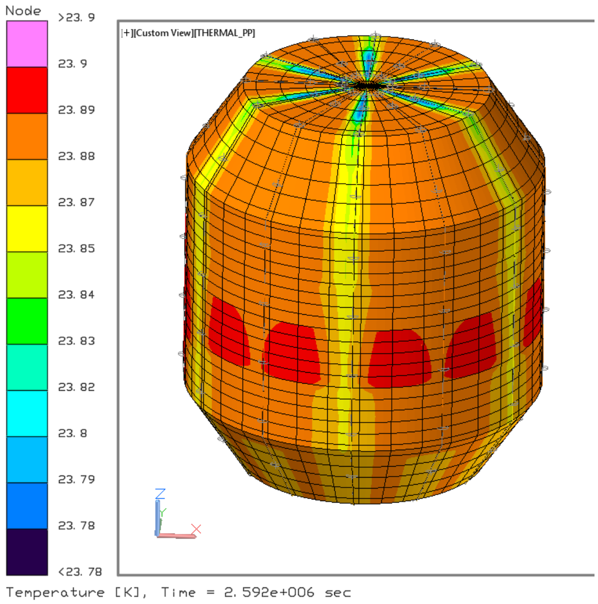

Figure 8. Tank wall temperature profile at 1-g.

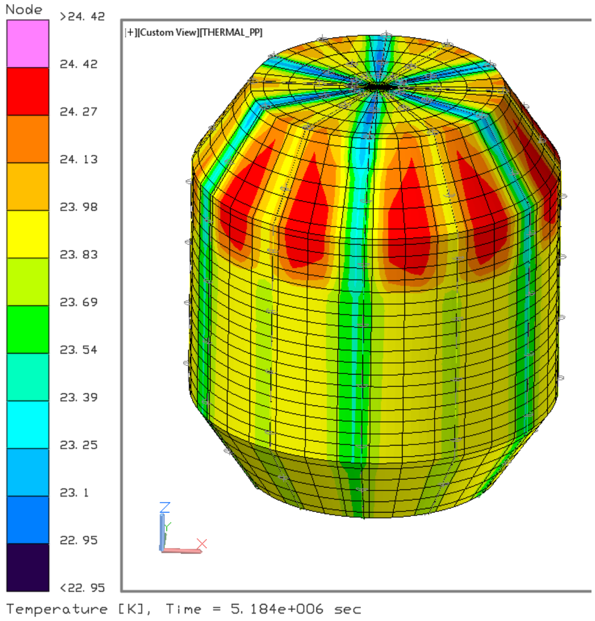

Figure 9. Tank wall temperature profile with Low-g HTC.

The heat flow associated with the temperature changes is indicated in Table 1. With the same environmental heat rate entering the tank in both cases, the reduced temperature tank wall in the low-g HTC case is noted by the 0.7 W drop in tank wall net heat when compared to the 1-g HTC case. Note that the nominal 1-g HTC case that the propellant is warming slightly, even though this was not noticed in the Fig. 7 pressure curve. There is additional cryocooler lift or heat removal in the low-g HTC case, which is realized by a decrease in the coolant gas temperature.

Table 1. System heat leak response to changing HTC's.

Heat	1*HTC (Watts)	0.01*HTC (Watts)
Environment Heat	96.8	96.8
Tank Wall Net Heat	0.03	-0.7
Cryocooler Lift	96.77	97.5

IV. SUMMARY

This Nuclear Thermal Propulsion broad area cooling zero boil-off analysis was performed to determine the fluid responsiveness to heat removal as a function of gravity level. In all cases, the hydrogen propellant was treated as a homogenous fluid, which is possible because of the presence of the broad area cooling system. An initial look at tank pressure response to a 5% oversized cryocooler system and a 5% undersized system with 1-g heat transfer coefficients was done. In both cases, tank pressure changes at a steady rate, enabling a straightforward control scenario and an effective power storage capability. As flight data shows lower heat transfer coefficients in reduced gravity, a comparison of low and nominal coefficients was made to understand the fluid response to the broad area cooling system operation. The indications are that the slower fluid response in low gravity is off-set by added tank wall cooling. This initial study of the fluid response to the cryocooler system shows an adequate tank pressure timeline response and an unimpeded ability of the cryocooler system to control the tank wall temperature.

ACKNOWLEDGMENTS

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