Thermo-physical performance prediction of the KSC Ground Operation Demonstration Unit for liquid hydrogen

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Abstract. NASA Kennedy Space Center (KSC) researchers have been working on enhanced and modernized cryogenic liquid propellant handling techniques to reduce life cycle costs of propellant management system for the unique KSC application. The KSC Ground Operation Demonstration Unit (GODU) for liquid hydrogen (LH₂) plans to demonstrate integrated refrigeration, zero-loss flexible term storage of LH₂, and densified hydrogen handling techniques. The Florida Solar Energy Center (FSEC) has partnered with the KSC researchers to develop thermal performance prediction model of the GODU for LH₂. The model includes integrated refrigeration cooling performance, thermal losses in the tank and distribution lines, transient system characteristics during chilling and loading, and long term steady-state propellant storage. This paper will discuss recent experimental data of the GODU for LH₂ system and modeling results.

1. Introduction
A recent report from NASA on the historical average loss of LH₂ through the entire Space Shuttle Program indicates that overall LH₂ loss in transit, chill-down of transfer system, tanker pressurization, the ground storage tank, chill-down of ground and flight system, and the external tank replenish are about 46% of total purchased fuel[1]. The NASA acknowledged needs of advanced ground operation technology for future spaceport that increases the efficiency of hydrogen operations to higher than 80%. NASA KSC initiated the GODU for LH₂ project to investigate alternative storage and distribution architecture for future cryogenic propellant operations, and demonstrate advanced cryogenic propellant handling operations of normal boiling point (NBP) and subcooled cryogenic hydrogen. The GODU for LH₂ is based on the principle that hydrogen losses can be eliminated by integrated refrigeration system in the storage tank. The oversized refrigerator allows for propellant densification and in situ liquefaction by placing cold heat exchanger in the LH₂ storage tank[2-4]. This active refrigeration concept has been successfully demonstrated at the FSEC[5] and the Korea Institute of Science and Technology (KIST)[6] as a laboratory scale hydrogen liquefaction and densification.
operation using a cryocooler. The GODU for LH\textsubscript{2} has expanded the scale and operations of the FSEC and the KIST demonstrations to much larger scale in refrigeration power and storage volume. The GODU for LH\textsubscript{2} consists of the reverse-Brayton helium refrigerator (Linde R1620), the 33,000 gallon horizontal cylindrical storage tank with a modified manway for heat exchanger and instrumentation feedthrough, the ‘whale skeleton’ structured heat exchanger, vacuum jacketed transfer lines, gaseous hydrogen venting and flare system, and LH\textsubscript{2} vaporizer\cite{3-4}. The main objectives of the GODU for LH\textsubscript{2} is to demonstrate zero loss storage and transfer of LH\textsubscript{2} at a large scale, hydrogen liquefaction using a close cycle helium refrigerator, hydrogen densification in the storage tank, low-helium usage operations and loading of flight tank. Figure 1 shows a photo of the GODU for LH\textsubscript{2} storage tank at the Hydrogen Technology Demonstration Site at the KSC.

Several modeling analyses were performed for cold heat exchanger and thermal behavior of LH\textsubscript{2} in the storage tank to provide heat exchanger design and system operation parameters of the GODU for LH\textsubscript{2}\cite{2-4}. A lumped thermal and fluid modeling analysis on the storage tank was performed for liquefaction and densification mode based on the storage tank dimension and the refrigerator performance\cite{7}. This lumped modeling analysis was able to predict (1) thermal losses of the storage tank, (2) thermodynamic condition of LH\textsubscript{2} in the storage tank during liquefaction and densification mode, and (3) transient behavior of two-phase hydrogen in the storage tank to predict operation time and fluid condition during liquefaction and densification. Recently, NASA KSC researchers have performed a series of experiments on the GODU for LH\textsubscript{2}, and have provided updated modeling parameters to FSEC. This paper discusses noticeable comparisons between thermal modeling analysis and experimental results of the GODU for LH\textsubscript{2}.

![Figure 1](image1.png)

\textbf{Figure 1.} The GODU for LH\textsubscript{2} storage tank at the Hydrogen Technology Demonstration Site at the NASA KSC.

\section*{2. Thermal modeling of the GODU for LH\textsubscript{2}}

A lumped thermal modeling analysis focuses on macroscopic thermodynamic conditions of gaseous and liquid hydrogen during in situ liquefaction and densification in the tank. Figure 2 shows schematics of a simplified lumped thermal model of the storage tank. When the storage tank is partially filled with gaseous and liquid hydrogen, total heat leaks to the storage tank have four simplified routes: (1) through the tank wall in the gaseous hydrogen region ($\dot{Q}_{wg}$), (2) through the tank wall in the liquid hydrogen region ($\dot{Q}_{wl}$), (3) through manway and instrumentation ($\dot{Q}_{manway}$), and (4) through the inner tank supports and supply/drain line penetrations ($\dot{Q}_{support}$). The heat leaks through the tank walls can be estimated by combination of natural convection heat transfer at near walls, conduction heat transfer through the wall, and multilayer insulation specification. The heat leaks through the manway and supports/line penetrations were previously estimated as $\dot{Q}_{manway} = 50$ W and...
\( \dot{Q}_{\text{support}} = 20 \text{ W} \) [3], and these values remain constants through the analysis. \( \dot{Q}_{\text{ref\_g}} \) and \( \dot{Q}_{\text{ref\_l}} \) are refrigeration loads absorbed by the heat exchanger in the gas and liquid region, respectively. Pressure, gas temperature distributions, liquid level in the tank are measured by various probes and sensors during each experiment.

Table 1 shows a summary of mass and energy balance equations for control volumes of gas and liquid region, and selected natural convection heat transfer correlation at the walls. The in situ liquefaction is performed at tank pressure, \( P \), while precooled or room temperature hydrogen gas (\( m_{\text{in}} \)) flows into the tank to compensate the condensed gas hydrogen to liquid (\( m_{\text{cond}} \)). At near ambient tank pressure, gaseous hydrogen in the gas region can be considered as an ideal gas. In the liquid region, LH\(_2\) is considered as incompressible liquid. In order to estimate heat leaks through the tank walls, \( \dot{Q}_{\text{w\_g}} \) and \( \dot{Q}_{\text{w\_l}} \), a set of mass and energy balance equations for the tank wall, MLI, and outer wall were combined into those for hydrogen, and were numerically solved at the same time to simulate thermal equilibrium of hydrogen and the tank walls. The natural convection heat transfer coefficient correlations in Table 1, the wall dimensions, and MLI specifications were adopted from previous analysis [3,7-10]. All the thermodynamic property information used in this analysis is from ‘Thermophysical Properties of Fluid Systems’ by NIST.
Experimental results and discussion

The NASA KSC has recently performed a series of experiments on the GODU for LH$_2$ using integrated refrigerator and heat exchanger. A chill-down process was performed by the Linde R1620 refrigerator and heat exchanger with hydrogen gas. Once the storage tank was cooled near liquid hydrogen temperature, 11,800 gallons of LH$_2$ was transferred from tankers to the storage tank via vacuum jacketed transfer lines. The evaporated hydrogen gas flow was measured at near ambient pressure to estimate total heat leak into the storage tank. Two in situ liquefaction tests were performed with and without warm hydrogen gas makeup feed. A boil-off test was performed without refrigeration cooling to obtain temperature and pressure rise profiles. These experiments produced several noticeable data that can be used for the modeling validation.

3.1. Heat leak estimation

Figure 3 shows estimated heat leak distributions by the lumped modeling in the gaseous and liquid region and available refrigeration power as a function of liquid level percent in the tank. The Linde R1620 refrigerator and heat exchanger with hydrogen gas. Once the storage tank was cooled near liquid hydrogen temperature, 11,800 gallons of LH$_2$ was transferred from tankers to the storage tank via vacuum jacketed transfer lines. The evaporated hydrogen gas flow was measured at near ambient pressure to estimate total heat leak into the storage tank. Two in situ liquefaction tests were performed with and without warm hydrogen gas makeup feed. A boil-off test was performed without refrigeration cooling to obtain temperature and pressure rise profiles. These experiments produced several noticeable data that can be used for the modeling validation.

### Table 1. Mass and energy balance governing equations for in situ liquefaction mode, and natural convection heat transfer correlations at the tank walls[3,7-10].

| Region   | Mass and energy balance equations |
|----------|----------------------------------|
| Gas      | \[
\frac{dm_g}{dt} = \dot{m}_{in} - \dot{m}_{cond}, \quad \frac{d(m_g u_g)}{dt} = \dot{m}_{in} h_{in} - \dot{m}_{cond} h_i + \dot{Q}_{w,g} + \dot{Q}_{manway} - \dot{Q}_{ref,g} \]
| Liquid   | \[
\frac{dm_l}{dt} = \dot{m}_{cond}, \quad \frac{d(m_l u_l)}{dt} = \dot{m}_{cond} h_i + \dot{Q}_{w,l} + \dot{Q}_{support} - \dot{Q}_{ref,l} \]
| Walls    | \[
Nu = \frac{h_w \cdot k_{H_2}}{D_{tank}} = 0.555 \, Ra^{1/4} \quad \text{for laminar} \\
Nu = \frac{h_w \cdot k_{H_2}}{D_{tank}} = 0.0210 \, Ra^{2/5} \quad \text{for turbulent} \\
where, \, Ra = Gr \cdot Pr, \quad Gr = \frac{g \beta (T_w - T_{H_2}) D_{tank}^3}{\nu^2} \]

Where, Nu is Nusselt number, Ra= Rayleigh number, Gr= Grashof number, and Pr= Prandtl number.

3. Experimental results and discussion

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3.1. Heat leak estimation

Figure 3 shows estimated heat leak distributions by the lumped modeling in the gaseous and liquid region and available refrigeration power as a function of liquid level percent in the tank. The Linde R1620 is known to produce 800 W of net refrigeration power at 20 K including connecting lines losses [3]. Differences between net refrigeration power and total heat leak become available cooling powers at given liquid level in the tank. When KSC transferred 11,800 gallons of LH$_2$ into the GODU for LH$_2$ tank, it converts to about 33 % liquid level in the tank. In the figure 3, total heat leak estimated at 33% liquid level shows 258.8 W of total heat leak including gas region, liquid region, support, manway and instruments. In fact, KSC measured the evaporated hydrogen gas flow as 260 SLPM at 45 K. This gives hydrogen mass flow rate of 21.7 g/min and total heat leak of 259.1 W. Therefore, the modeling shows very good agreement with measured total heat leak at given liquid level.
3.2. Liquefaction estimation

Figure 4 shows recent liquefaction and boil-off test results conducted at the KSC with the GODU for LH2 storage tank. Once 11,800 gallons of LH2 was loaded into the tank, the tank was stabilized with exhaust valve opened for a while, then sealed off. The refrigerator began to cool the tank without GH2 feed between t=120 hr and t=200 hr. At t=200 hr, warm GH2 feed was initiated and it continued at nearly constant flow of average 250 g/min at 15.1 psia until t=700 hr. Then, both GH2 feed and the refrigerator were stopped and boil-off test was initiated from t=700 hr. Six temperature probes were vertically installed at the center of the storage tank. TT3 and TT4 show saturation temperature of LH2 at the measured tank pressure, while other 4 probes show gas temperatures during various condition of the tank. One can expect liquid level increase during the liquefaction period between t=200 hr and t=700 hr due to constant GH2 feed.

Figure 5 shows the required liquefaction time profiles to obtain specific liquid level at various liquefaction pressures. From this plot, one can estimate liquefaction time required for certain liquid level, or liquid level accumulated for certain period of liquefaction time. For example, current GODU for LH2 will take about 210 days to liquefy 100 % fill level. Figure 5 can also be effectively used for cases that liquefaction begins at certain liquid hydrogen level in the tank. The initial 11,800 gallons of LH2 in the tank gives 33 % liquid level in the tank. For 500 hrs (=20.8 days) of liquefaction at 15.1 psia constant pressure in figure 4, one can expect about 44 % of liquid hydrogen level in the tank in figure 5. In fact, the LH2 level at t=700 hr can be roughly estimated from temperature profiles of TT4 and TT9 that the LH2 level should be somewhere between TT4 (saturated liquid temperature) and TT9 (superheated temperature). Therefore, the liquefaction modeling demonstrates its useful capability of liquid level estimation or time estimation required for specific liquid level in the storage tank.

Figure 3. Estimated heat leak distributions as a function of liquid hydrogen level in the storage tank.
Figure 4. Hydrogen temperature distribution in the tank (center area) during LH$_2$ loading (t < 120 hr), liquefaction without GH$_2$ feed (120 hr < t < 200 hr), liquefaction with GH$_2$ feed (200 hr < t < 700 hr), and boil-off test (t > 700 hr).

Figure 5. Required liquefaction time as a function of liquid level at various pressures.
4. Conclusion
As a part of efforts in modernizing LH₂ systems at the NASA KSC, the GODU for LH₂ demonstrates advanced cryogenic propellant handling techniques to enhance overall spaceport efficiency. FSEC has developed a lumped thermal modeling tool to predict various performances of the GODU for LH₂ storage tank. The modeling tool predicts overall thermal losses and transient behavior of the storage tank during in situ hydrogen liquefaction and long-term storage operation modes. Recent experimental data for total heat leak measurement and in situ liquefaction test show good agreements with the modeling analysis results. FSEC will continue to improve prediction accuracy and usefulness of the modeling with experimental updates on densification mode in the GODU for LH₂.

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