TRANSIENT MODELING OF LARGE SCALE INTEGRATED REFRIGERATION AND STORAGE SYSTEMS

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INTRODUCTION

• In 2015 CryoTestLab engineers tested a large scale Integrated Refrigeration and Storage (IRAS) system for liquid hydrogen at NASA Kennedy Space Center
  ❖ 125,000 liters of LH₂
  ❖ Zero-loss tanker offloads, long duration zero boiloff (ZBO), liquefaction, densification with slush production

• **IRAS** = storage tank + internal heat exchanger + cryogenic refrigeration system
  ❖ Control via direct addition and removal of thermal energy (heat) as opposed to addition and removal of mass
  ❖ Full control over the bulk fluid properties anywhere along the saturation curve
INTRODUCTION

• **GODU-LH2**
  - IRAS tank with custom-built internal tubular heat exchanger
  - Linde Cryogenics LR1620 helium refrigerator (390 W or 850 W @ 20 K with and w/o LN₂ precooling)

• 3x temperature rakes to map hydrogen temperature profile, 20 total silicon diodes

• Redundant pressure transducers

• Successfully tested at 4 different fill levels: 33%, 46%, 67% & 100%

• **Excellent data for anchoring analytical models!**
INNER TANK INSTRUMENTATION

**Elevations**

<table>
<thead>
<tr>
<th>Elevations</th>
<th>m</th>
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<tbody>
<tr>
<td>TT3</td>
<td>0.57</td>
</tr>
<tr>
<td>TT4</td>
<td>0.92</td>
</tr>
<tr>
<td>TT9</td>
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<td>TT10</td>
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<td>TT16</td>
<td>2.12</td>
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<tr>
<td>TT20</td>
<td>2.72</td>
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</table>

**Accuracies**

- **Diodes:** ±0.5 K from 450 K to 25 K, and ±0.1 K from 25 K to 1.5 K
- **Transducers:** ±6.89 kPa (1% of full scale)
TRANSIENT DATA SET

- Particularly interested in predicting the hydrogen temperature and pressure trends during transient periods.

- Densification test data at three different fill levels was used to anchor analysis:
  - Closed tank (no mass exchange)
  - Depressurization and temperature drop as heat is removed
  - Specific regions chosen for consistent and uninterrupted refrigerator operation

Cryogenics Test Lab

Analysis

Region

46% Full Testing

67% Full Testing

100% Full Testing

Pressure, kPa (abs)

Temperature, K

Analysis Region

100 hours

Closed tank (no mass exchange)

Depressurization and temperature drop as heat is removed

Specific regions chosen for consistent and uninterrupted refrigerator operation
TRANSIENT MODELS

Two different models were developed, based on two different high level assumptions:

1. The entire tank, both liquid and vapor, was fully saturated throughout the test
   - Simpler scheme, first one developed
   - Hydrogen properties could be defined by just one parameter
   - Temperature and pressure of the liquid and vapor would be equal

2. The bulk liquid was subcooled, with a finite layer of saturated liquid separating it from the saturated vapor
   - Evolved from saturated model at 100% fill level
   - Saturated layer suppressed heat transfer, slowing depressurization rate
   - Refrigerator lift cooled the bulk liquid below the boiling point → heat transfer through the layer
   - Entire HX was submerged

Useful convergence parameter
TRANSIENT MODELS

Model Similarities

- Lumped node, forward stepping in time
- Constructed in Excel, utilizing Visual Basic & RefProp v8
- Any tank volume, geometry, or stored fluid
- Constant and variable GHe inlet properties
- All lift took place in the liquid region
- GHe outlet temp from HX equaled the LH₂ temp
- 15 minute time increments
- Heat leaks constant

Saturated Model

\[ \dot{Q}_{\text{VL, supply}} \rightarrow \text{from different analysis (36 W)} \]

Subcooled Model

\[ \dot{Q}_{\text{HL,vap \& liq}} \rightarrow \text{from boiloff calorimetry of IRAS tank (function of fill level)} \]
SUBCOOLED MODEL DETAILS

- Assumed pure solid conduction through the saturated liquid layer
- $\Delta T$ across the layer, but constant nodal temperatures for subcooled LH$_2$ & vapor

**How is $L_{SL}$ determined?**

- $L_{SL}$ estimated by equating heat transfer into the vapor and through the layer during steady state $\rightarrow |\dot{Q}_{SL}| = |\dot{Q}_{HL,vap}| = \frac{\lambda_{SL}A_{LV}}{L_{SL}} (T_{vap} - T_{liq})$
  - 100% fill level ZBO-PC data used
  - $A_{LV}$ estimated from tank geometry and liquid level ($A_{LV} \approx 45.5$ m$^2$, assumed constant)
  - $L_{SL} \approx 35$ mm (assumed constant)
SATURATED MODEL RESULTS

- Good prediction at 46% full for variable GHe properties!
- Constant GHe properties is probably a bad assumption
- Tank not saturated at 100% full

Subcooled model
SUBCOOLED MODEL RESULTS

- Only variable GHe properties shown
- Much better prediction of both depressurization & temperature drop!
  - Avg. $\Delta P$ between data and model = -0.06 kPa
  - Absolute temperature error = 0.03%
- Model also run at 67% full
  - Better accuracy than saturated model, but still less than other fill levels
DISCUSSION & TAKE-AWAYS

• Results appear to suggest that the tank was fully saturated at lower fill levels, but deviated as the liquid level increased → function of the unique GODU-LH2 system, or more fundamental?
  ➢ Is it, or can it be affected by heat exchanger design, refrigerant flow path, tank geometry, fluid species, etc?

• Both models closely predicted the transient data, but was dependent on fill level → is a generalized “universal” scheme possible?

• Approaches seem to be applicable to any scale IRAS system, but some information is required a priori → heat leak estimations, refrigerator performance numbers, etc.

• Good basis for future examinations, but more experimental testing and analytical study is necessary!
THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

Storm clouds over GODU-LH2 test site
June 2016