TRANSIENT MODELING OF LARGE SCALE INTEGRATED REFRIGERATION AND STORAGE SYSTEMS

27th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2018
ICEC 27-ICMC 2018
Oxford, United Kingdom, September 3-7, 2018

Adam M. Swanger

NASA Kennedy Space Center
Cryogenics Test Laboratory
KSC, FL 32899 USA
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

Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2)
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

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)

Elevations

<table>
<thead>
<tr>
<th>Elevations</th>
<th>Meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT3</td>
<td>0.57 m</td>
</tr>
<tr>
<td>TT4</td>
<td>0.92 m</td>
</tr>
<tr>
<td>TT9</td>
<td>1.24 m</td>
</tr>
<tr>
<td>TT10</td>
<td>1.54 m</td>
</tr>
<tr>
<td>TT15</td>
<td>1.85 m</td>
</tr>
<tr>
<td>TT16</td>
<td>2.12 m</td>
</tr>
<tr>
<td>TT20</td>
<td>2.72 m</td>
</tr>
</tbody>
</table>
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
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

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

Subcooled Model

\[ \dot{Q}_{HL,\text{vap} \& \text{liq}} \rightarrow \text{from boiloff calorimetry of IRAS tank (function of fill level)} \]
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 $\rightarrow |\dot{Q}_{SL}| = |\dot{Q}_{HL,\text{vap}}| = \frac{\lambda_{SL} A_{LV}}{L_{SL}} (T_{\text{vap}} - T_{\text{liq}})$
  - 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% fill
  - 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