Liquid Nitrogen Line Chilldown Experiments in Reduced Gravity

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2016 American Society for Gravitational and Space Research
Introduction

- Chill down = process of cooling hardware down to cryogenic temperatures so vapor free liquid can flow from storage tank to engine or receiver tank
- Transfer lines connect cryogenic storage tanks to:
  - Launch pads
  - In-space engines
  - Receiver tanks, on the ground, and in space (depots)
- Simple energy balance on transfer line:
  \[ Q_{\text{flow}} = Q_{\text{line}} + Q_{\text{parasitics}} \]
  \[ \text{where } Q_{\text{flow}} = \int_{t_0}^{t_{\text{SS}}} (m(h_{\text{exit}} - h_{\text{inlet}})) \, dt, \quad Q_{\text{line}} = \int_{t_0}^{t_{\text{SS}}} mc_p \frac{dT}{dt} \, dt, \quad \text{and } Q_{\text{parasitics}} = \int_{t_0}^{t_{\text{SS}}} (\dot{Q}_{\text{rad}} + \dot{Q}_{\text{cond}} + ...) \, dt \]
- To achieve vapor-free liquid flow at exit, subcooled portion of flow energy must exceed parasitic heat
Problem Statement/Motivation

- Popular design codes GFSSP and SINDA FLUENT
- Large discrepancies between vertical data and current SINDA correlations:
  - Groeneveld or Bromley for FB
  - Gambill for CHF
  - Chen for CHF
- Room temperature correlations do not match well with cryogenic data
  - Based on room temperature fluids (perform worse against quantum fluids)
  - Based on heated tube experiments, not quenching
- Ultimate desire is to develop set of cryogenic “universal” correlations for both quenching and heated tube configurations
- Recently completed parametric LN2 chilldown test series completed in 2014/2015 at UF
- 211,000 cryogenic quenching data points
- Sparse historical quenching data sets in literature

Cryogenic fuel depots will enable long duration human and robotic missions past LEO

Efficient chilldown and transfer methods are required

High accuracy, efficient tools required to model two-phase flow boiling/heat transfer + minimize propellant consumption

Penalty for poor models results in higher
- Margin (ex. carry extra propellant)
- Safety factor (ex. thicker, heavier insulation)
- Cost in design (Current projected cost to launch and store propellant in LEO: $12-15,000/kg LH2)
Flight Hardware

- Flights onboard a C9 aircraft (10^{-2} g for 23-25s)
- 363 kg rig
- 54x3 (up, down, horizontal) 1-g tests, 10 10^{-2} g tests
- 73 kg/m^2s < G < 1619 kg/m^2s (2800 < Re < 170000)
- 0 K < (T_{sat} - T_{inlet}) < 14 K
- Test section 57.2cm long, 1.27cm OD
- Tc stations 14.9cm, 40.9cm from inlet

K bottle (NASA Provided)

Burst Disk Setting
BD1 – 200psig

Relief Valve Settings
 RV1 – 125psig
 RV2 – 125psig
 RV3 – 125psig
 RV4 – 125psig
 RV5 – 125psig
 RV6 – 125psig

Pressure Regulator Setting
PR1 – 0 to 100psig
PR2 – 0 to 125psig

Vacuum Pump

Flowmeters

Vacuum Chamber

Dewar

Pressure

PT Power Supply
Effect of Flow Direction (Upward vs. Downward)

- 3 pairs of chilldown curves, Re = 6000, 33000, 170,000

- Low to Intermediate Range (0 < Re < 33000)
  - Wall temperature decreases at a faster rate for upward flow vs. downward flow

- Highly Turbulent (Re>170,000)
  - no distinction between flow directions
Effect of Flow Direction (Upward vs. Downward)

- Film boiling dominates LN2 chilldown

**For low Re flows**

- During film boiling in upward flow:
  - $F_B$ aligned with motion of bulk fluid
- During film boiling in downward flow:
  - $F_B$ on vapor is fighting against inertia of bulk fluid

- Therefore, for the same $G$, vapor velocity is larger in upward vs. downward flow
- Convection between vapor and wall is dominate heat transfer during chilldown, upward flow will chill system down faster than downward flow
Effect of Flow Direction (Upward vs. Downward)

For high Re flows

- Buoyancy force $\ll$ Bulk inertia of fluid
- Net difference in vapor velocities caused by $F_B$ is negligible
- Therefore, no difference in chilldown at high Re

Implication

- Beyond a certain critical $G$, effect of flow direction is negligible
Low Gravity Test Results

**Trends**

- Chilldown time $\alpha$ Re
- HTC $\alpha$ Re
- Fluctuations in pressure due to phase change instabilities caused by large density differences
Effect of Gravity on Chilldown

For low Re flows
- Chilldown rate more affected by g
- Low-g chilldown slower than all 1-g cases
- Q: U>D>H>Low-g

For higher Re flows
- LFP reduced in low-g (26K lower)
- Curves begin merge to as inertial forces dominate over buoyancy forces

Implication
- Beyond a certain critical G, effect of gravity on chilldown is negligible
Conclusions & Future Work

1. Two-phase flow routines used in popular thermal/fluid design codes (GFSSP, SINDA) do not match at all with cryogenic quenching data in LH2, LN2
   - Overpredict heat transfer by as much as a factor of 200
   - Penalty for over-prediction is launching/storing more propellant in LEO

2. Trends for low-g (vs. 1-g)
   - (although not shown) virtually no temperature stratification in low-g
   - Slower chilldown rates in low-g
   - Lower film boiling HTCs in low-g
   - LFP reduced in low-g
   - @ High Re (> 50,000), curves are indistinguishable, g doesn’t matter
   - Increasing G and level of subcooling both lead to faster chilldown rates
   - Trends with cryogens qualitatively agree with storables
Conclusions & Future Work


**Future Work**

1. Complete 1-g LN2 and LH2 chilldown data analysis
2. Assemble GRC, UF, and historical data, begin “universal” quenching correlation development
3. Parabolic flight to test film boiling modifications (early spring, 2017)
Thank you!

Questions/Comments?