Thermal Modeling of Zero Boil Off Tank Experiment

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Outline

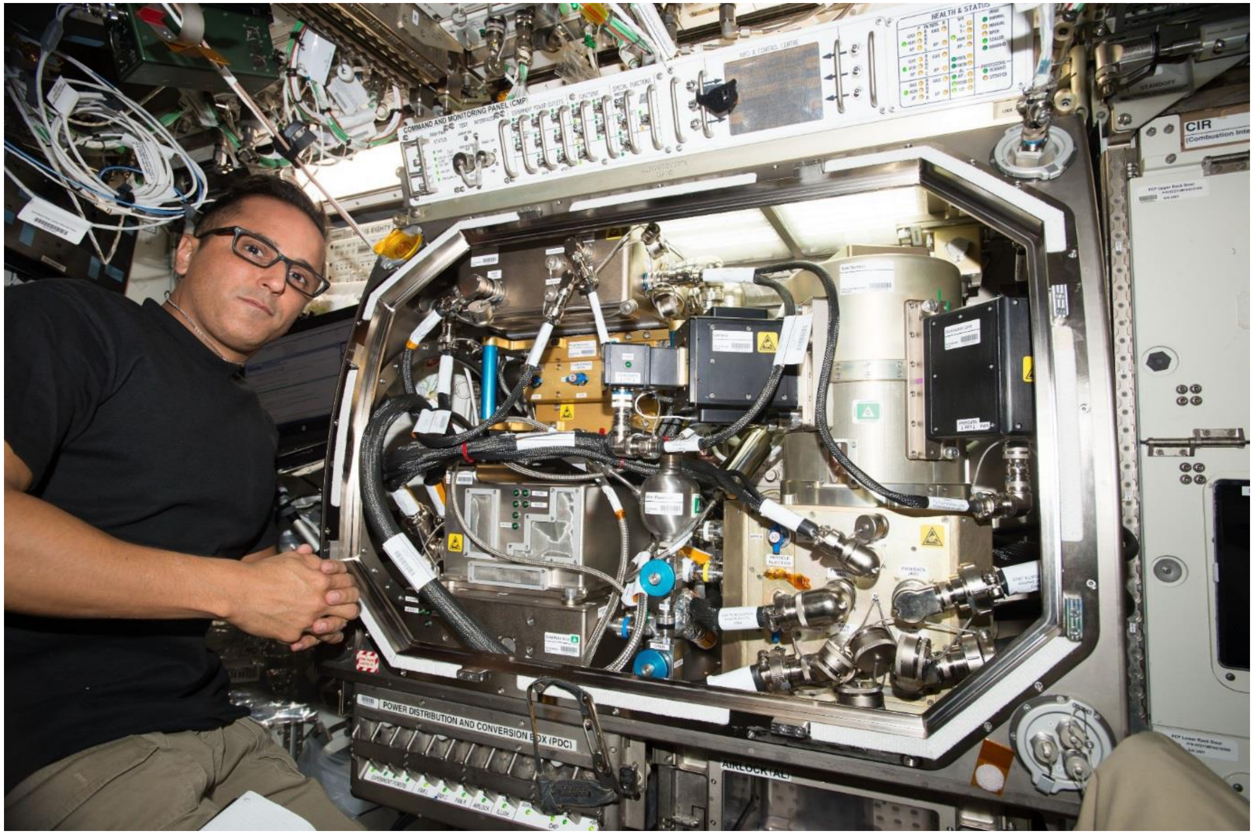
- Background
- ZBOT Experiment Description
- Thermal Modeling & Validation
  - 1G Vacuum-Jacket Heating
  - 1G Strip Heater
  - Microgravity Strip Heater
- Conclusions & Future Work

Background

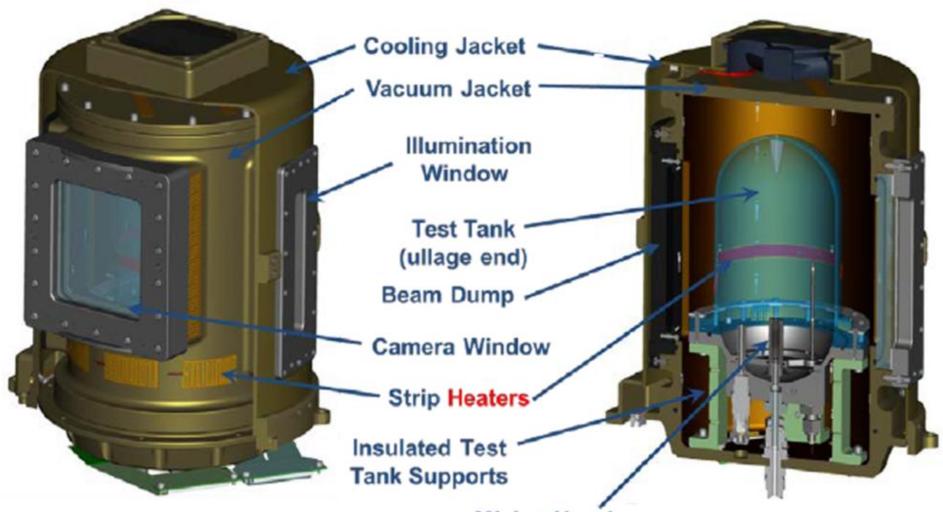
- Cryogenic Fluid Storage in microgravity is crucial to the development of future long-term space missions
- Zero Boil-Off Pressure Control:
  - High cost savings
  - Various design/implementation issues
    - Two phase flow in microgravity, heat & mass transfer interactions
- Creating accurate thermal models of cryogenic fluids is a key step in developing these systems

Zero Boil-Off Tank Experiment

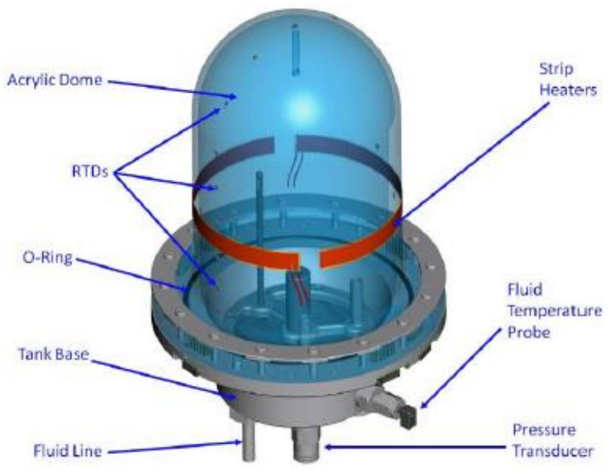
- Designed to investigate two-phase pressurization/depressurization in microgravity
  - Working Fluid: Perfluoro-normal-Pentane (PNP)
  - Experiment conducted on ISS, Fall 2017



ZBOT Test Setup



ZBOT Test Tank inside the Vacuum Jacket

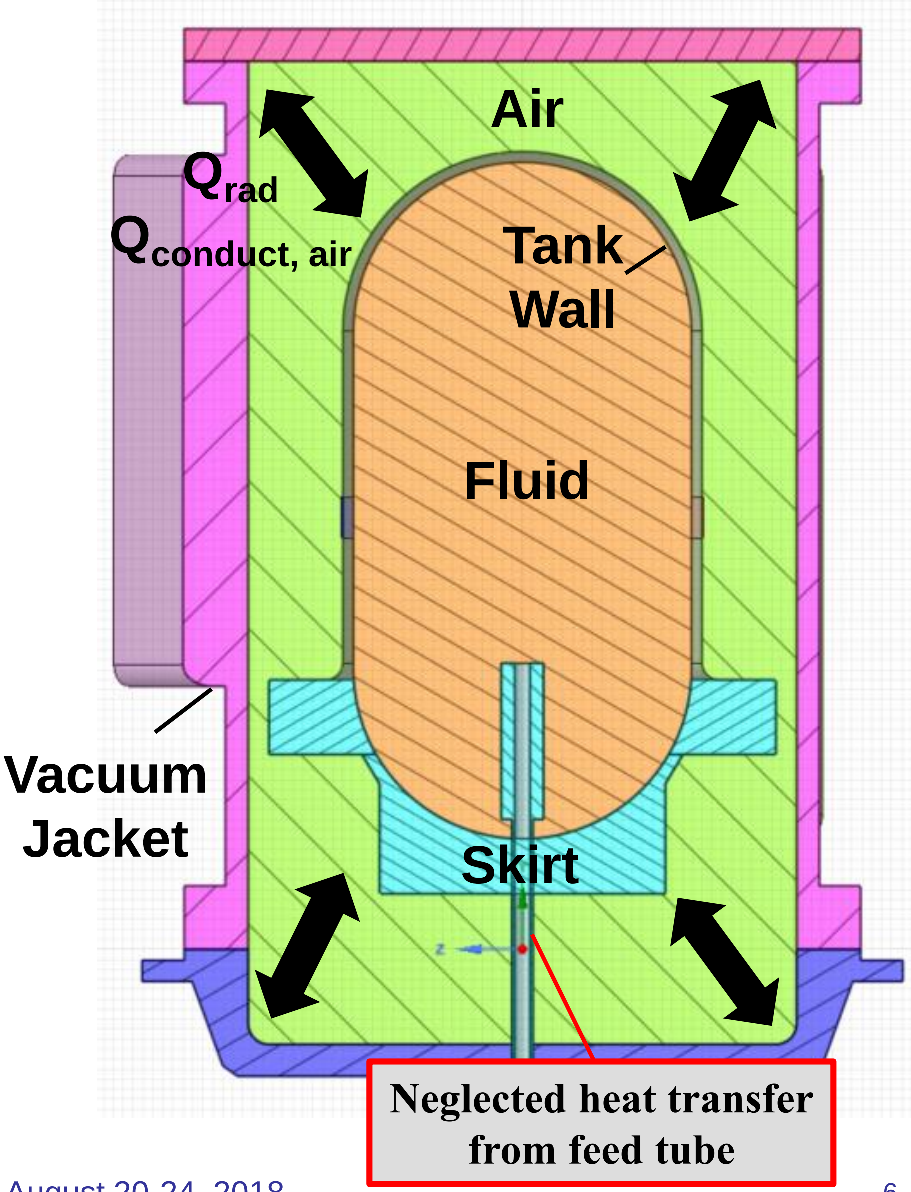


Acrylic Test Tank Dome

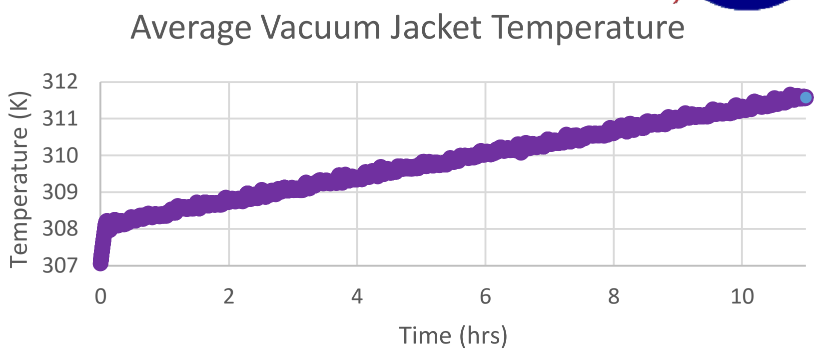
- ZBOT-1
  - Natural Convection
  - Forced Mixing
  - Microgravity Evolving Phase Distribution
  - Free Surface Dynamics/Ullage Dynamics
  - Evaporation/Condensation
  - Superheating/Nucleate Boiling in Microgravity

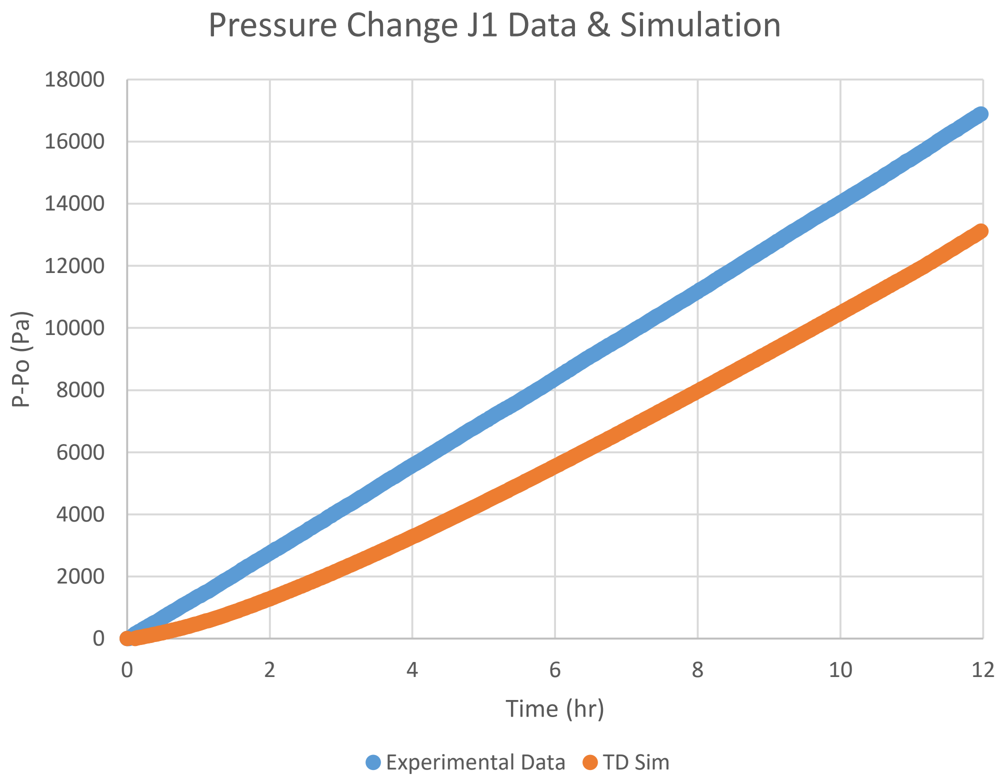
Thermal Model

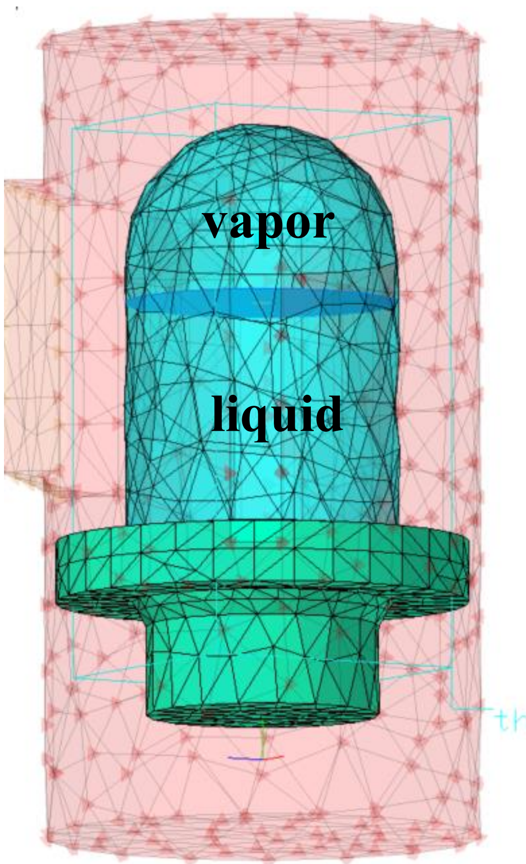
- Geometry simplified in SpaceClaim
- Imported into Thermal Desktop
  - Heat transfer from VJ to Tank Wall/Skirt via
    - Radiation from VJ
    - Conduction from VJ to Tank Wall/Skirt, through Air
    - Conduction along Tank Wall, VJ wall
    - Measured VJ temperatures from experiment used as Boundary Condition in model



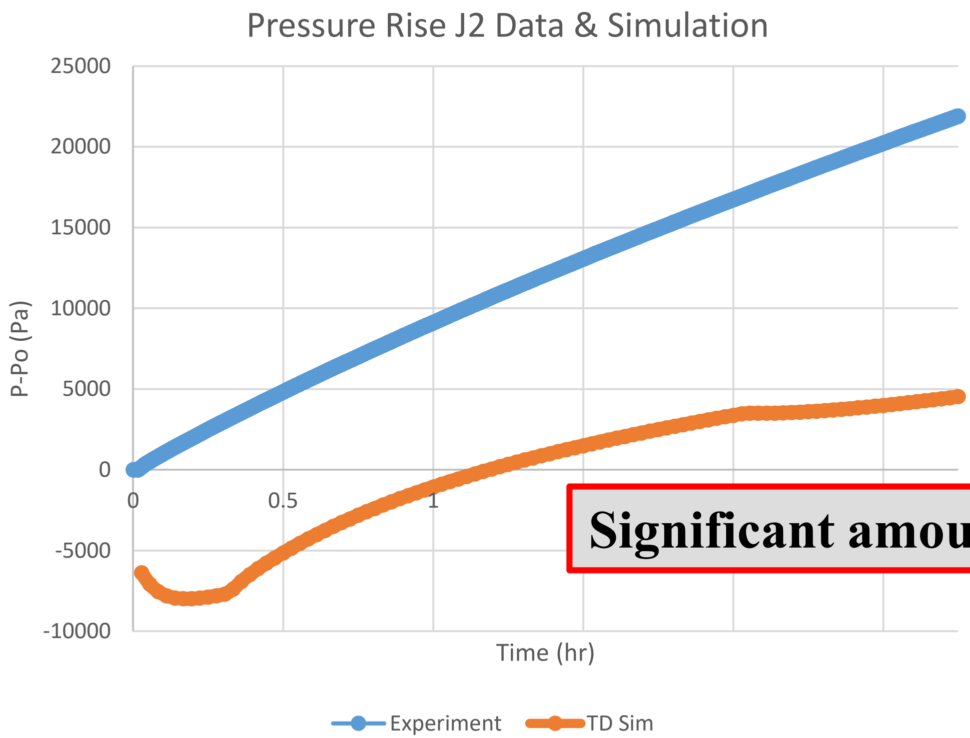
- Thermal Desktop and SINDA/FLUINT
  - Vacuum Jacket Heating
  - Q = 0.5W
  - Fill Level = 70%

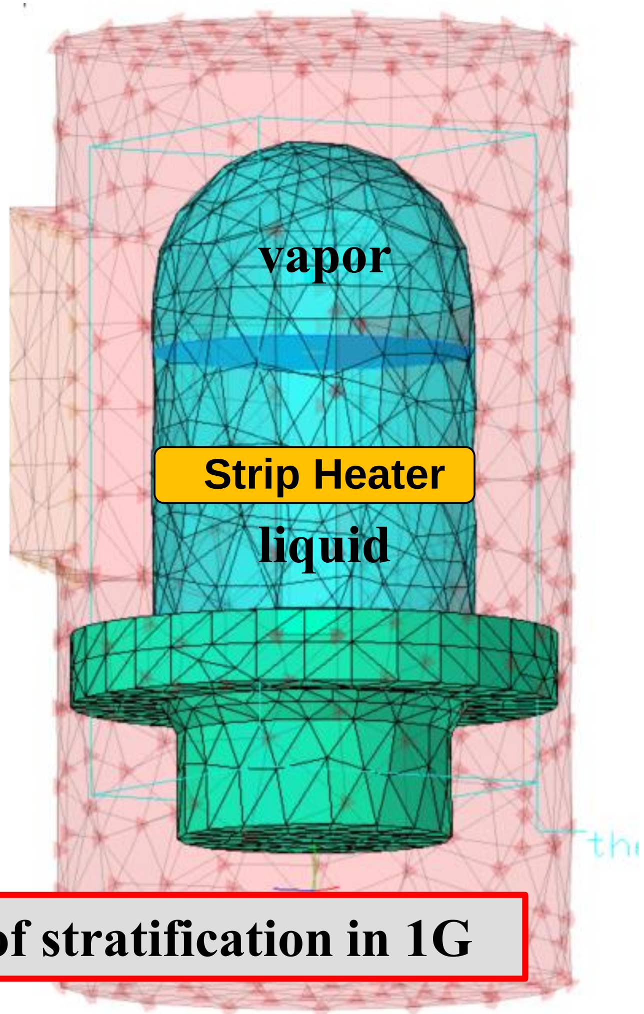






- Thermal Desktop and SINDA/FLUINT
  - Q = 0.5W
  - Fill Level = 90%
  - Two Fluid Lumps





Significant amount of stratification in 1G

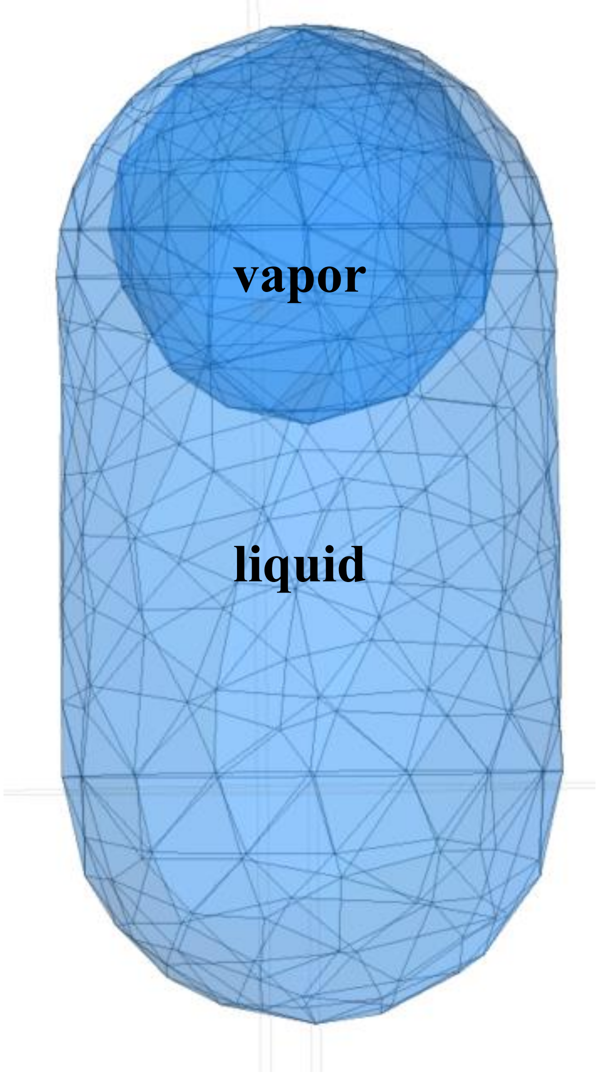
Thermal Model- Microgravity

- Microgravity, Strip Heater case
  - Q = 0.5W
  - Fill Level = 70%
- Vapor/Liquid imported from initial Fluent 2D CFD model
- Liquid modeled as solid finite element
  - 561 nodes
- Single fluid lump for vapor
- Heat and mass transfer between Liquid/Vapor:
  - Schrage Equation

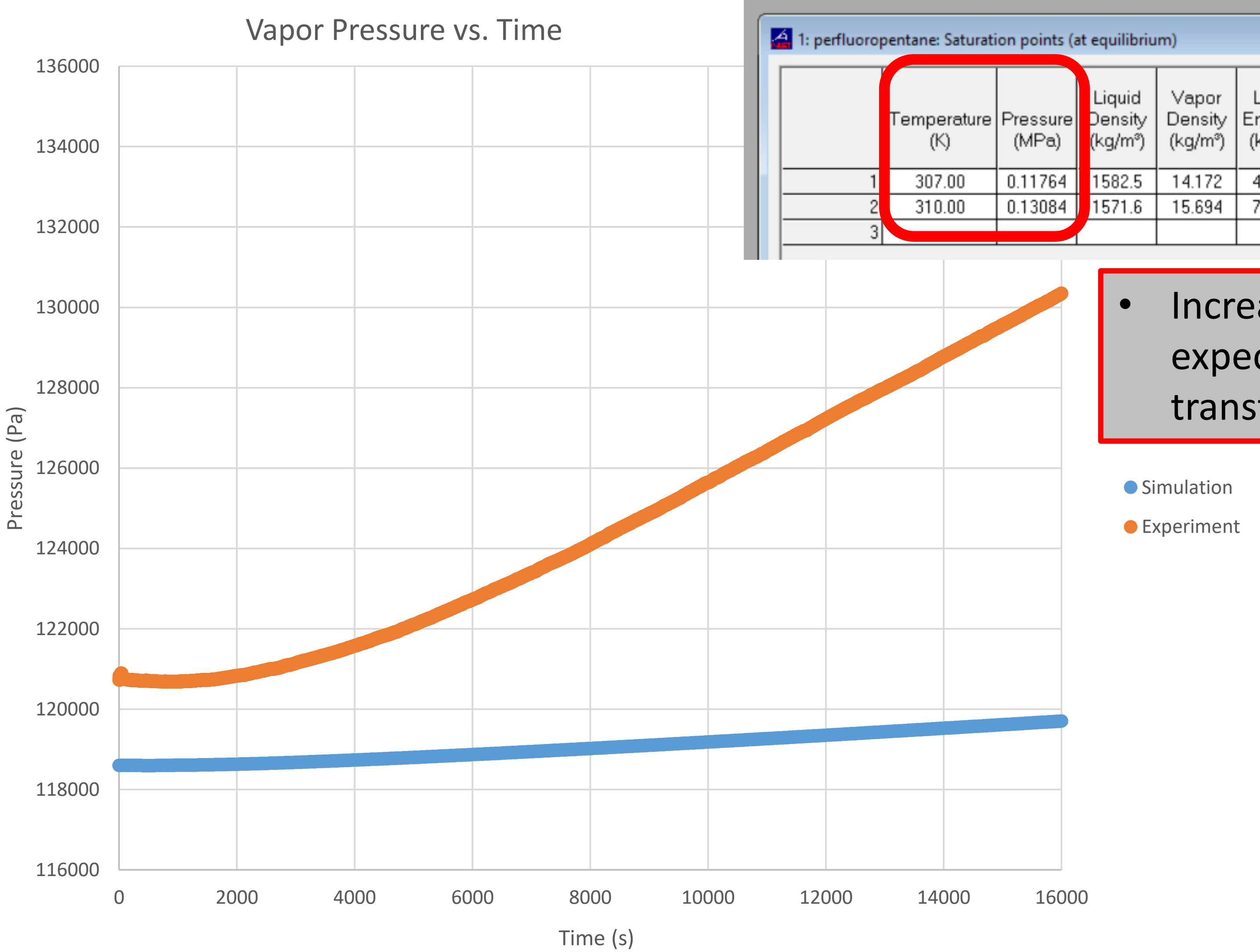
$$|\dot{\mathbf{m}}| = \left(\frac{2\sigma}{2-\sigma}\right)\left(\frac{M}{2\pi R}\right)^{1/2}\left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}}\right)$$

$$Q = \dot{m} h_{vap}$$

σ = accommodation coefficient



Model Validation: μG Self-Pressurization, Strip Heater – No Mass Transfer

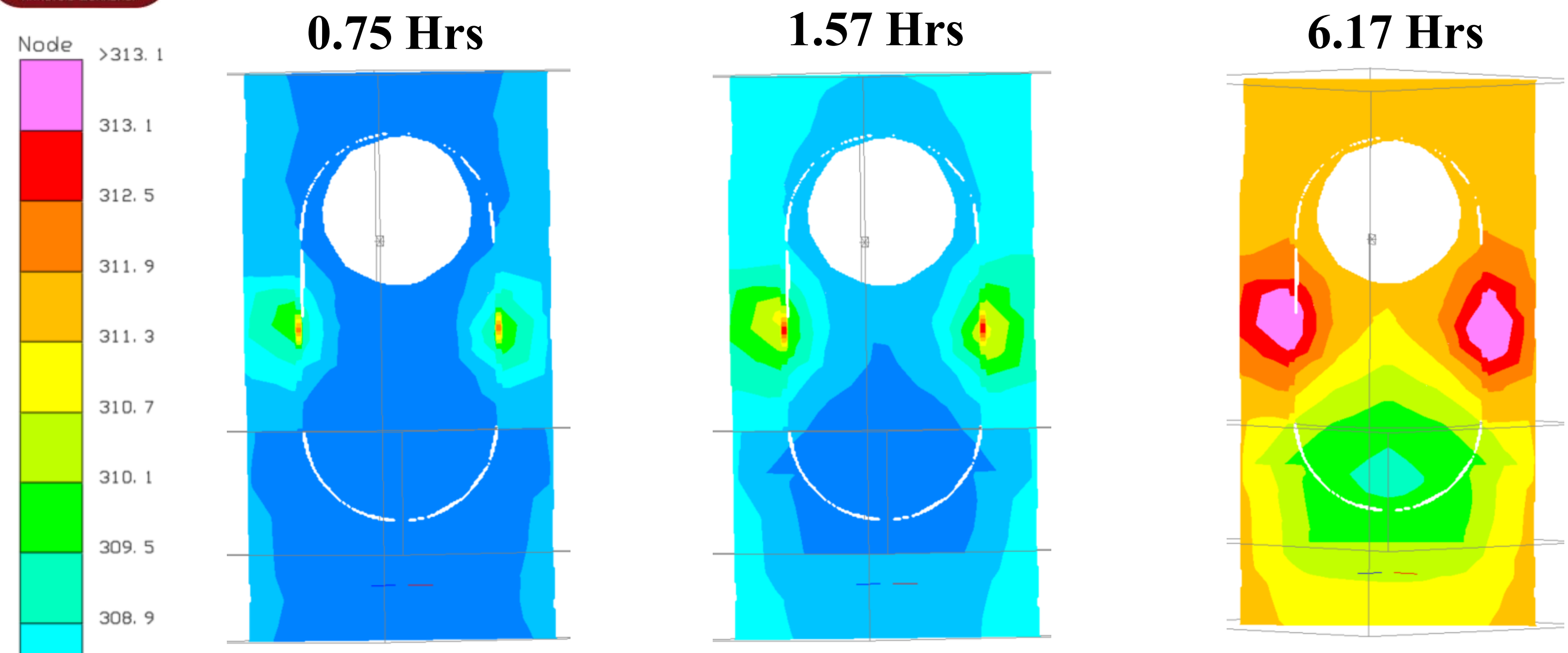


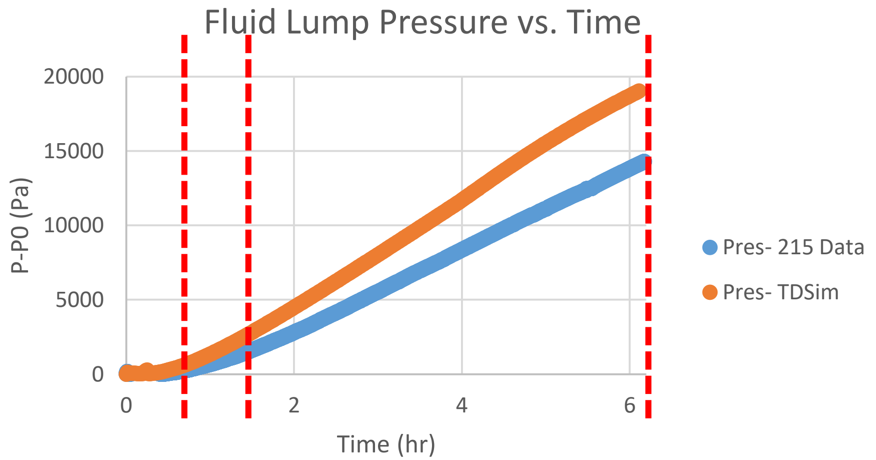
1: perfluoropentane: Saturation points (at equilibrium)

	Temperature (K)	Pressure (MPa)	Liquid Density (kg/m³)	Vapor Density (kg/m³)	Liquid Enthalpy (kJ/kg)	Vapor Enthalpy (kJ/kg)	Liquid Entropy (kJ/kg-K)	Vapor Entropy (kJ/kg-K)
1	307.00	0.11764	1582.5	14.172	4.4809	95.043	0.014660	0.30965
2	310.00	0.13084	1571.6	15.694	7.7811	97.356	0.025331	0.31428
3								

- Increase of 13,200 Pa expected w/ mass transfer

Model Validation: μG Self-Pressurization, Strip Heater, W/ Mass Transfer





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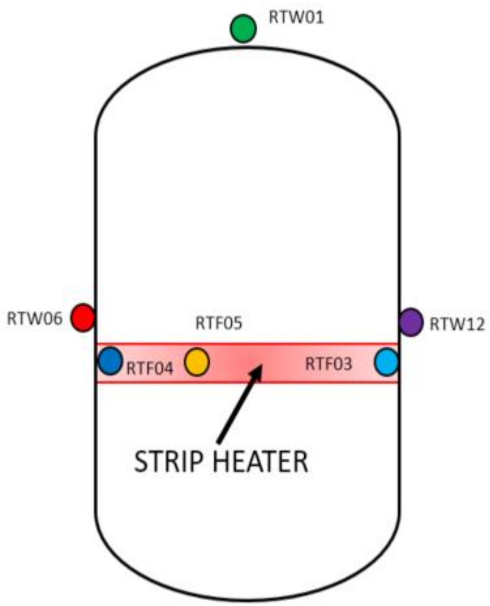

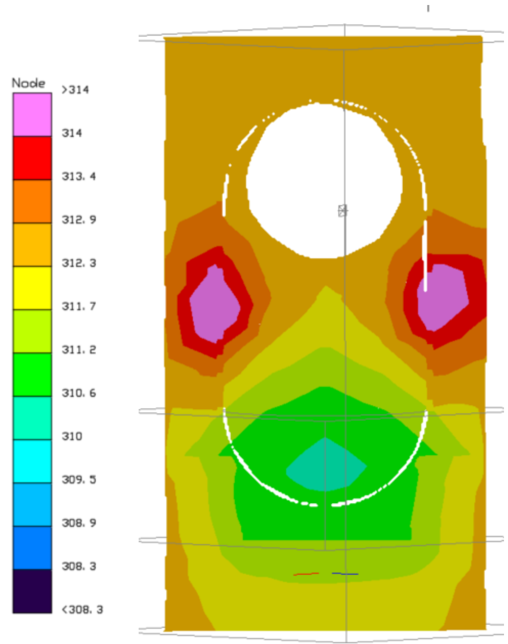

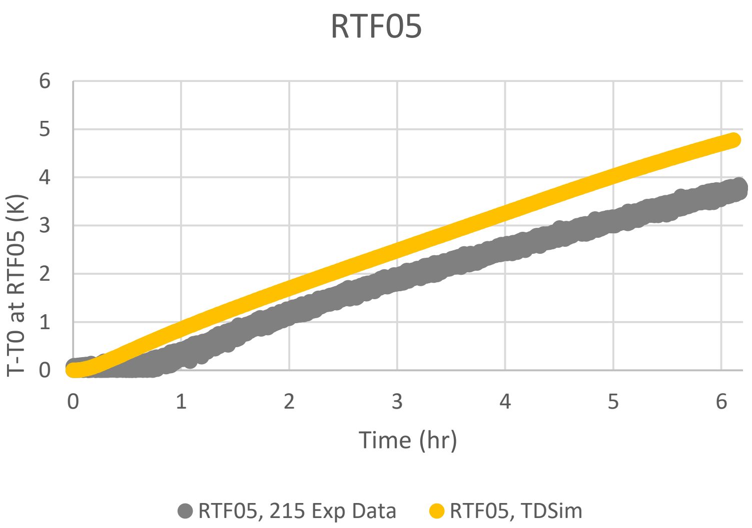

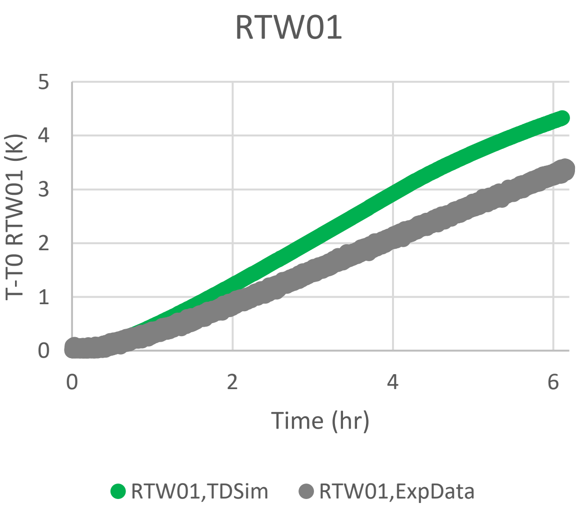

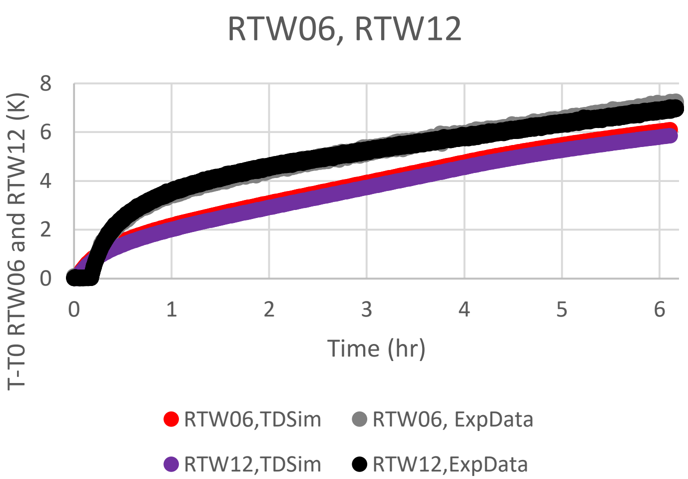

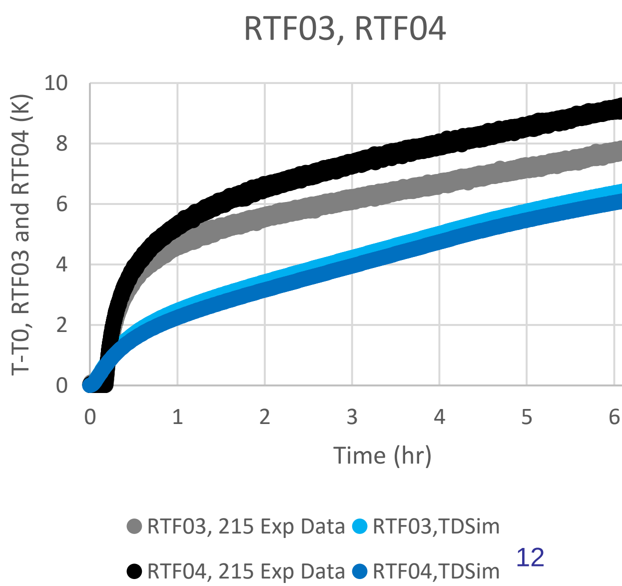

Conclusions

- Vacuum Jacket Heating Case, 1G:
  - TD two-node fluid model able to match experimental pressure rise within 10%
    - Uniform heating of tank produces more uniform liquid temperatures within tank, causing more accurate results in model
- Strip Heater Case, 1G:
  - TD two-node fluid model does poor job at matching experimental pressure rise due to localized heating of tank wall
- Strip Heater Case, μG:
  - TD fluid model with finite element liquid able to match experimental pressure rise within 30%, initial CFD results match experimental data within 10%

Future Work

- Modeling of 1G case with Strip Heater
  - Direct comparison with microgravity case
- Refine mesh of liquid finite element model
  - Model won't run if accommodation coefficient is too large, CFD approach also had this problem
  - CFD results using VOF can't resolve the grid at the LVI, have to use sharp interface
  - Very fine grid near the LVI would allow wider range of accommodation coefficients
- Comparison of ZBOT results with cryogen in microgravity
- Further modeling efforts to focus on replication of larger tank in microgravity environment

Acknowledgements

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