Validation of Pressure Control in a Flight-scale Liquid Hydrogen Tank using a Spray Bar

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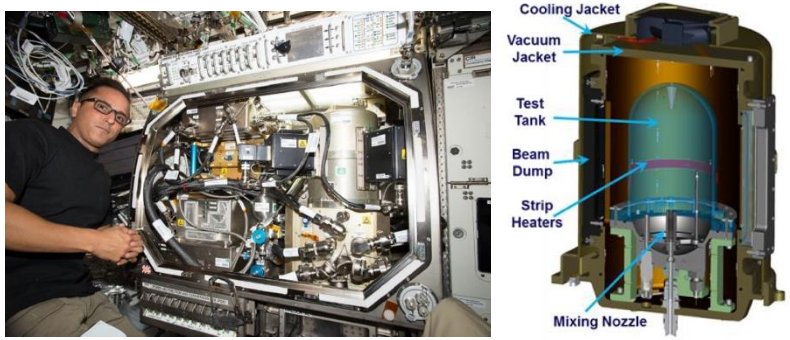
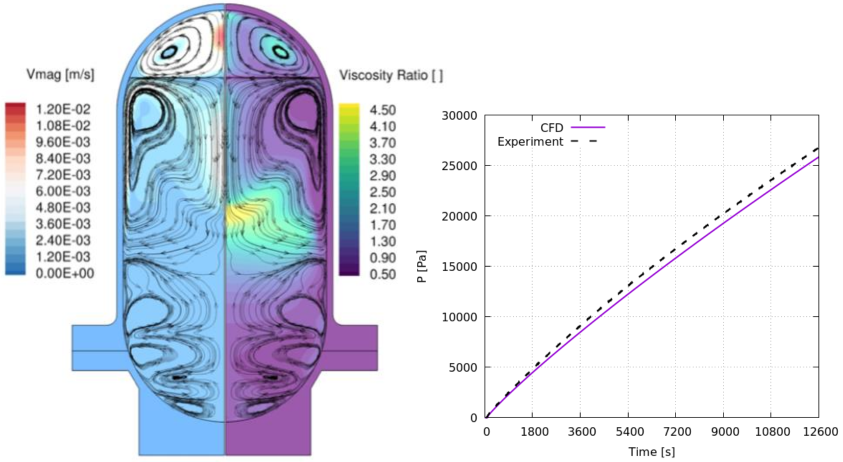
Background

- Managing cryogens is a critical technology for NASA's Artemis and future human space flight missions
- Cryogenic fluid management (CFM) challenges
  - Storage and delivery: evaporative loss due to heat leakage, liquid location tracking
  - Pressure control: pressurization, depressurization, cryocoolers
  - Tank filling/draining: draining and pressurization, jet and spray injection filling
- NASA's CFM Modeling Portfolio develops, enhances and validates computational fluid dynamic (CFD) and nodal tools for mission and operations design
- Fluid Dynamics Branch (ER42) at NASA Marshall Space Flight Center (MSFC) supports several CFM projects using CFD
  - Human Landing System (HLS), Commercial Lunar Payload Services (CLPS), Space Launch System (SLS), etc.
- ER42 has been validating Loci-Stream-VOF CFD solver to support current and future missions



Zero Boil-off Tank (ZBOT) Experiment[1]



Self-pressurization of Zero Boil-off Tank (ZBOT)

CFM modeling validation at NASA MSFC using CFD

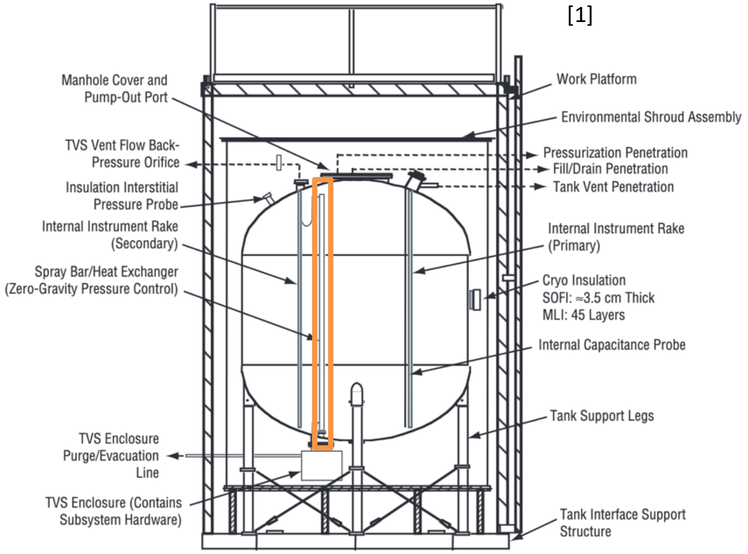
[1] M. Kassemi, S. Hylton and O. Kartuzova. "Zero-Boil-Off Tank (ZBOT) Experiment – Ground-Based Validation of Two – Phase Self-Pressurization CFD Model & Preliminary Microgravity Results," AIAA 2018-4940. 2018 Joint Propulsion Conference. July 2018

Acknowledgement: NASA MSFC and GRC's CFM Portfolio teams for helpful discussions/inputs

Test Set-up

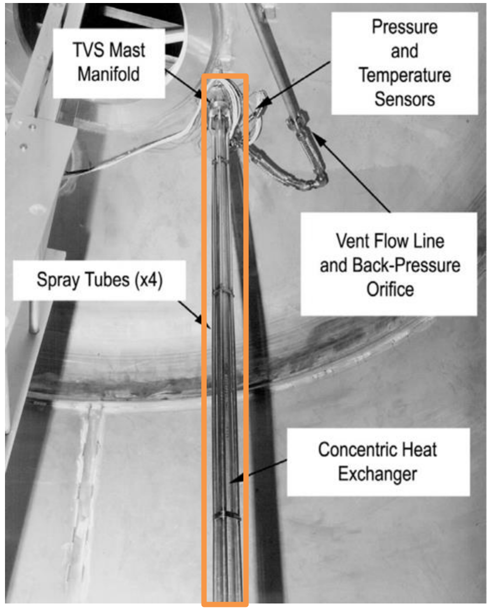
- Performed at NASA MSFC test stand 300 during 1996-1998 using MHTB (Multi-purpose Hydrogen Test Bed) tank
- 5083 aluminum double-domed cylindrical tank with 3.05 m diameter and 3.05 total height with 2:1 oblate hemispheres
- The tank is housed in a vacuum chamber and the heat leaks are characterized with boil-off tests and temperature measurements
- Spray bar TVS (thermal venting system) concept for pressure control
- Two vertical rakes house 24 temperature probes

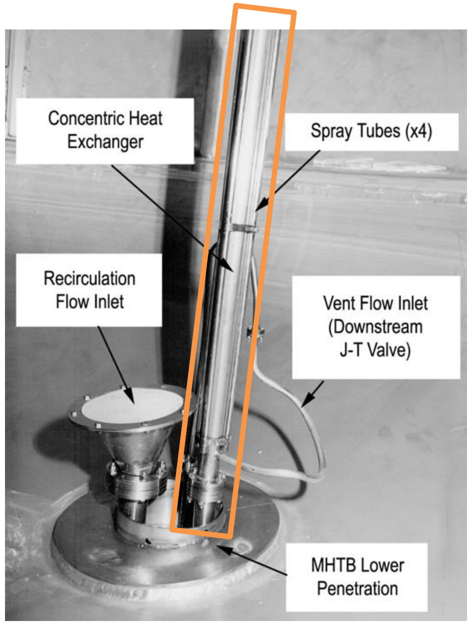
[1]

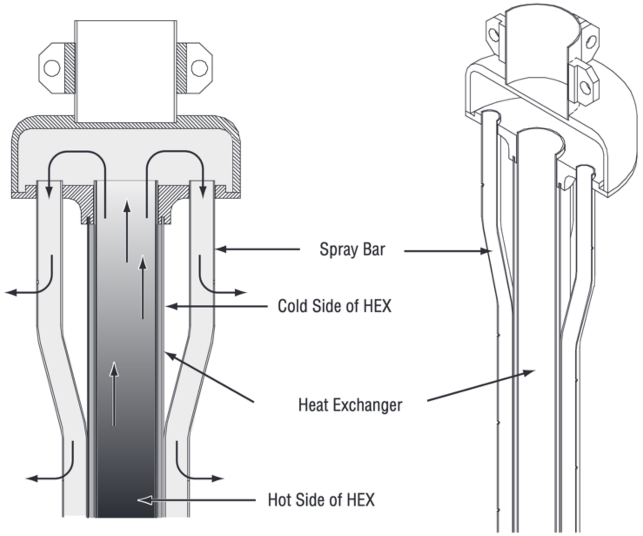


[1]

[1] Hastings, L.J., Flachbart, R.H., Martin, J.J., Hedayat, A., Fazah, M., Lak, T., Nguyen, H., Bailey J.W., 'Spray Bar Zero-Gravity Vent System for On-Orbit Liquid Hydrogen Storage", NASA TM-212926, 2003







Test Procedure and Computational Model

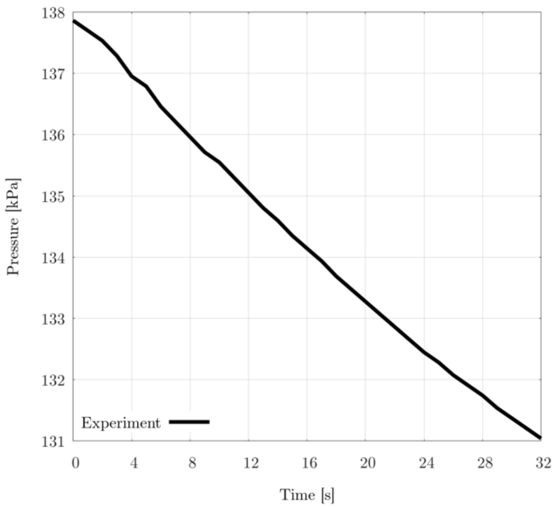
Spray bar cooling operation

- Tank is locked up and self-pressurizes until upper pressure limit of 137.9 kPa is reached
- Spray bar is turned on at constant mass flow rate of 0.136 kg/s at injection velocity of 6.4 m/s and operated until lower pressure limit of 131 kPa is reached

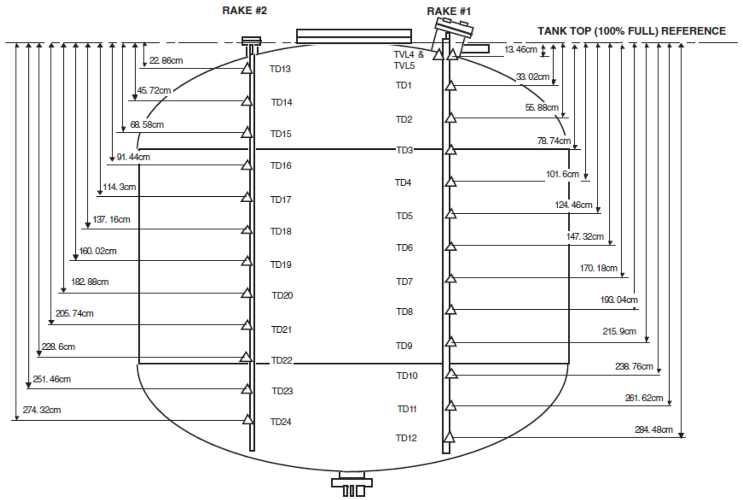
Computational Model

- Coupled Eulerian-Lagrangian modeling
- 90-deg sector domain
- Mesh and timestep insensitive predictions
    - 1e-4 m resolution required normal to the gas-liquid interface
- Second order spatial scheme
- Implicit second order time integration

Pressure Transience

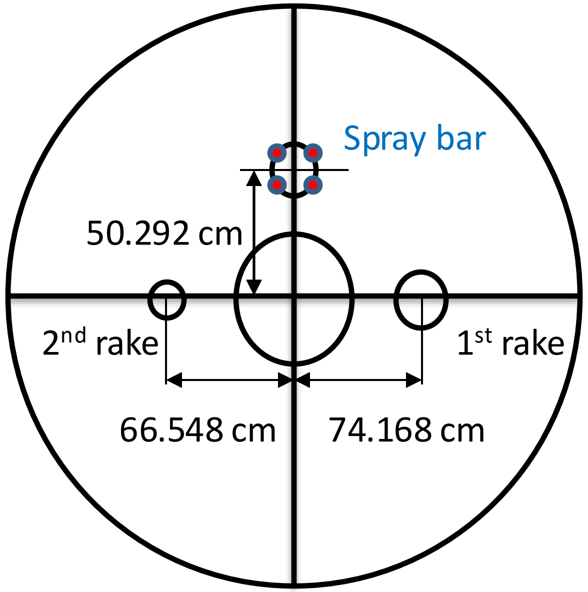


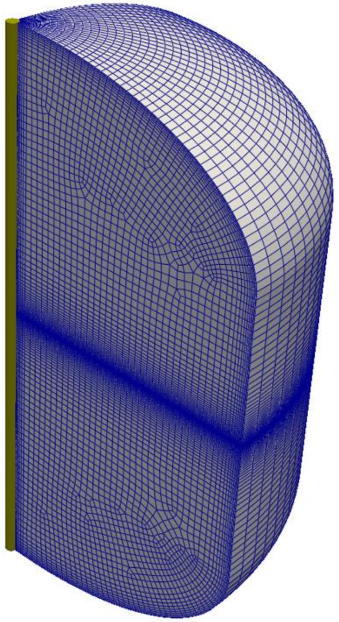
Temperature Rakes



[1]

Top View of the Tank





90-deg Computational Domain with Mesh

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[1] Hastings, L.J., Flachbart, R.H., Martin, J.J., Hedayat, A., Fazah, M., Lak, T., Nguyen, H., Bailey J.W., 'Spray Bar Zero-Gravity Vent System for On-Orbit Liquid Hydrogen Storage", NASA TM-212926, 2003

Computational Model

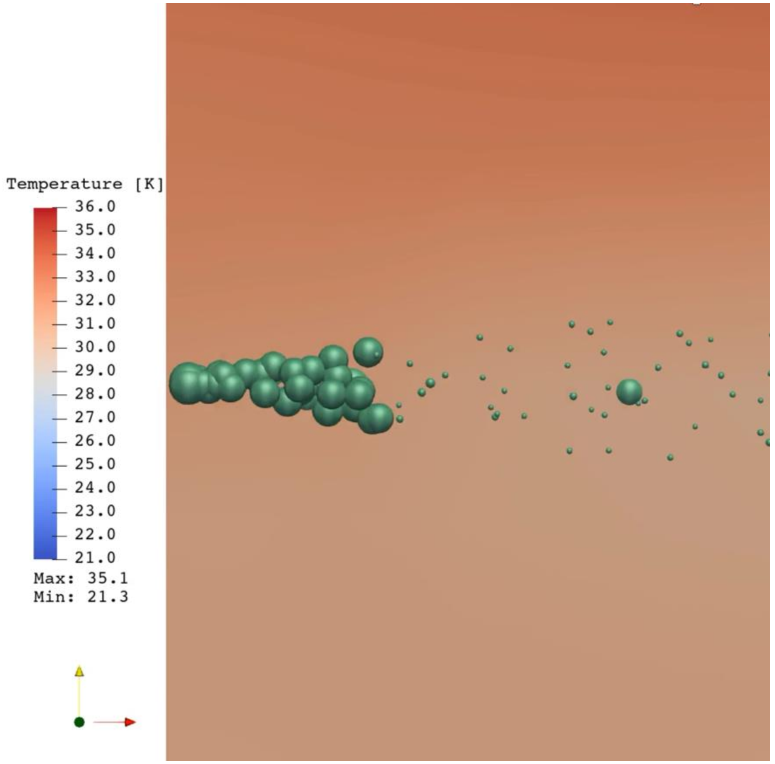
Eulerian Model

- Hybrid RANS/LES turbulence modeling with sharp interface method
- Interface turbulence transport modeling – Wall-like turbulence on gas side of the interface
- Thermal equilibrium and Hertz-Knudsen-Schrage's kinetics-based phase change model

Lagrangian particle modeling: Monte-Carlo modeling of multiphase flow

- Spray cannot be resolved in Eulerian phase - tracked using Lagrangian particles
- Momentum coupling: Clift-Gauvin
- Energy coupling: Ranz-Marshall
- Particle breakup: $P_{br} = f(We, We_c, d_{br})$
    - $We_c = f(Re_p, Oh)$, $d_{br} = d(d_p, We, Oh)$
- Droplet-droplet interaction (O'Rourke's) model: $E_{coal} = f(d_{p1}, d_{p2}, We(u_{rel}))$
    - coalescence or scattering based on collision Weber number, velocity vectors, and droplet size
- Particle phase change: Thermal equilibrium and Hertz-Knudsen-Schrage model
- Turbulence scattering: Sawford's acceleration scattering model

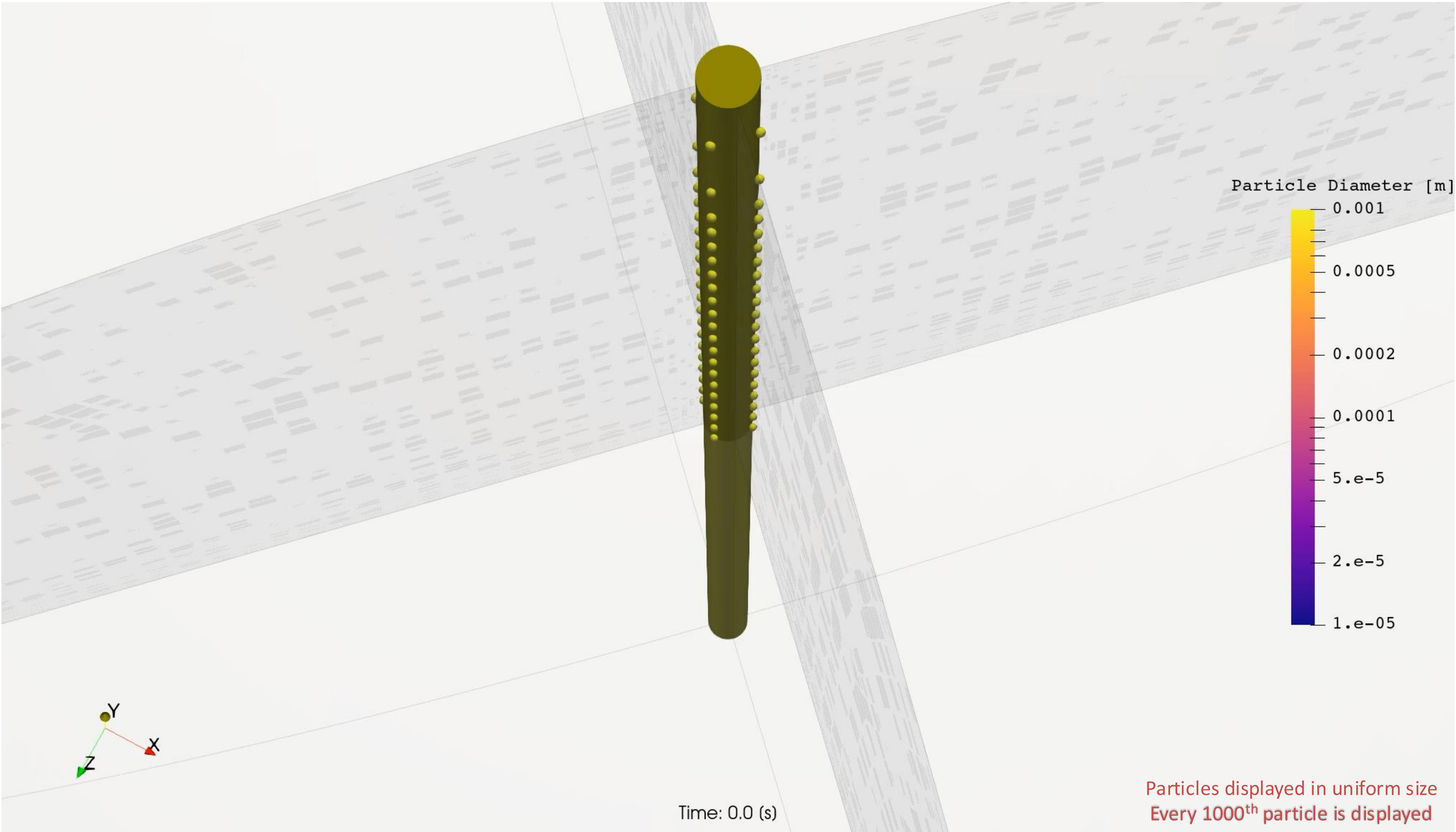
Single MHTB Spray Breaks up with Lagrangian Spray Break-up Model



Particles with injection diameter of 1.7 mm are scaled 4x for visualization

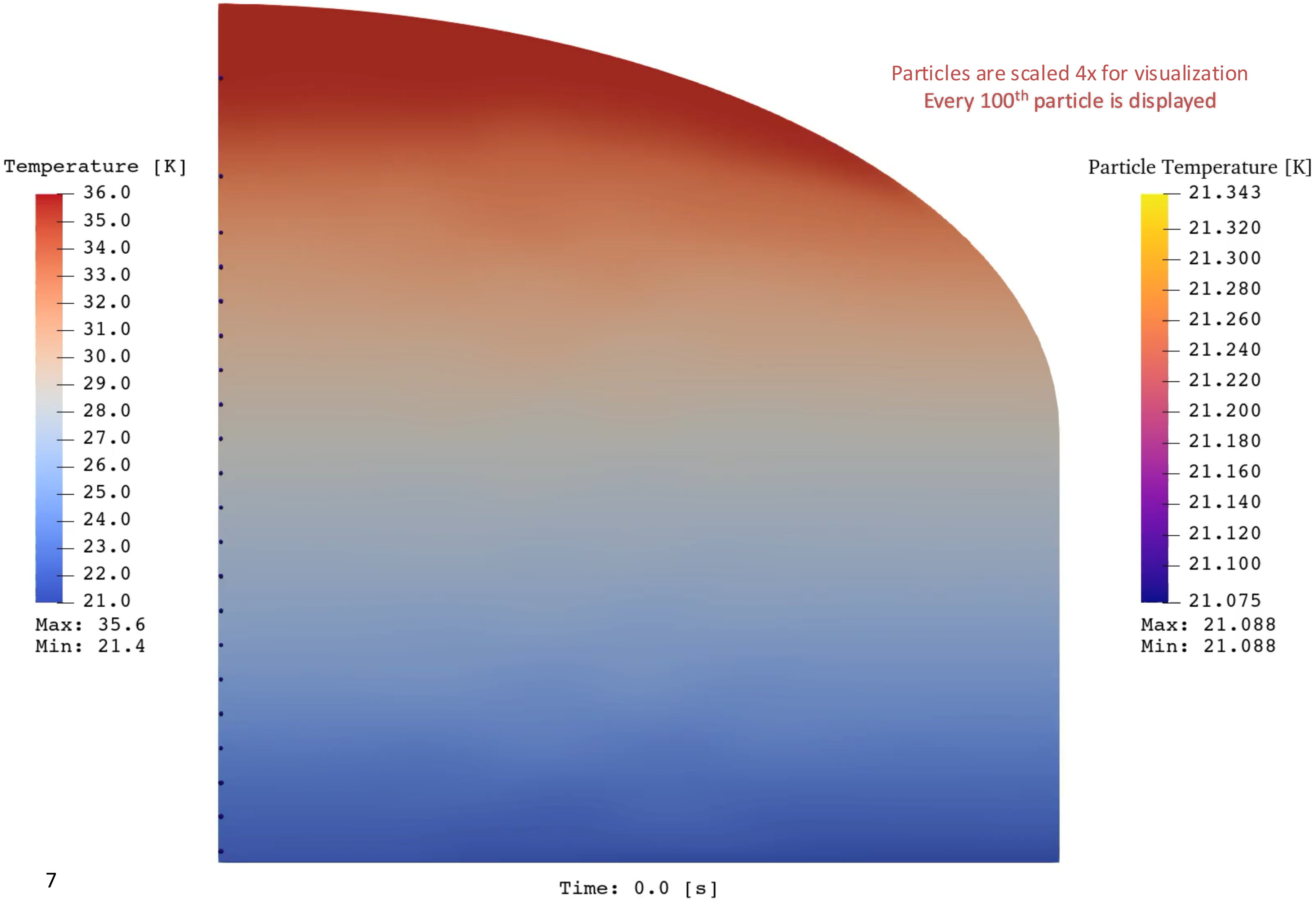
Every 100th particle is displayed

Particle Break-up Strongly Influences Depressurization Rate



Particles displayed in uniform size
Every 1000th particle is displayed

Particle Phase Change and Temperatures

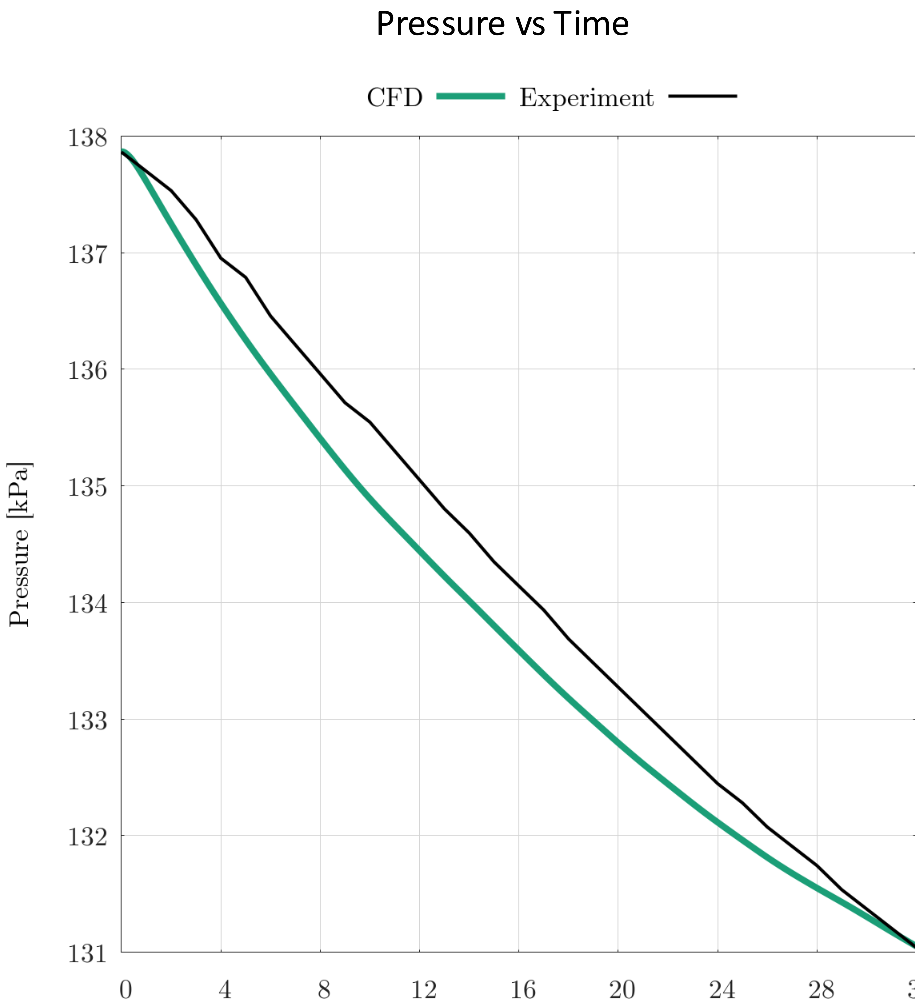


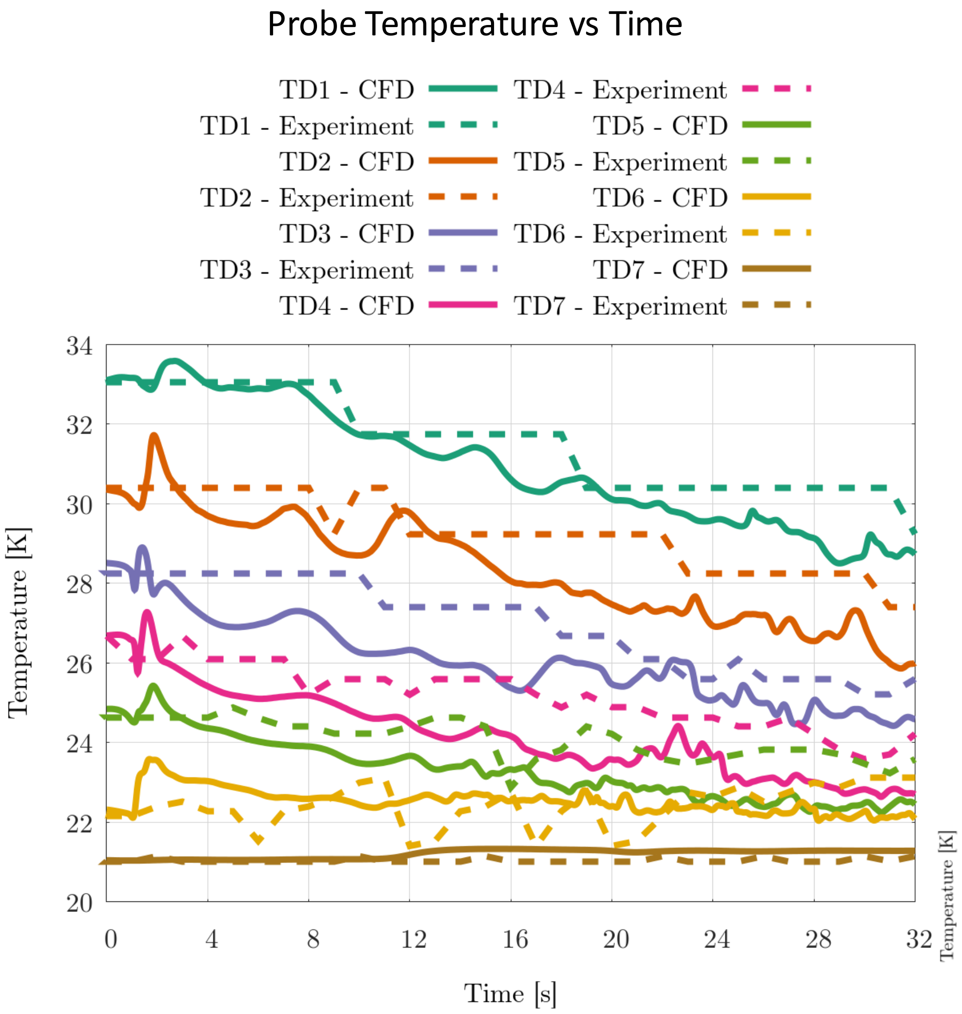
Particles are scaled 4x for visualization

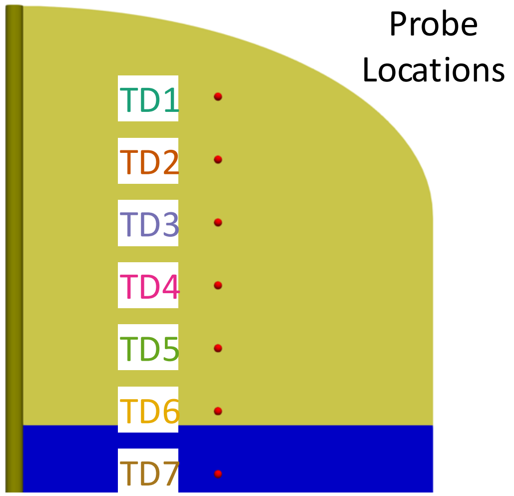
Every 100th particle is displayed

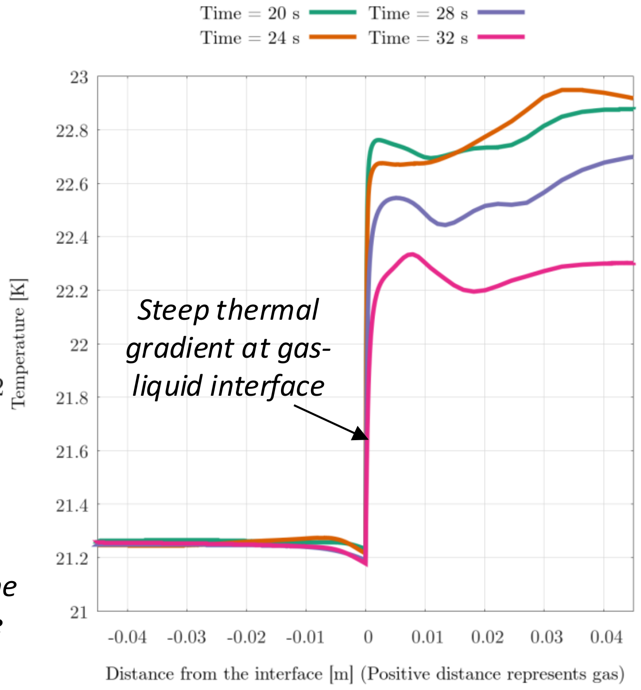
- "Thermal evaporation" phase change model ensures that particle phase change is limited by energy exchange between the particle and ullage gas
- For physically accurate phase change modeling, particle temperature is not allowed to exceed saturation temperature determined by ullage pressure

Validation – Pressure/Temperature Comparisons


Pressure vs Time


Probe Temperature vs Time


Probe Locations

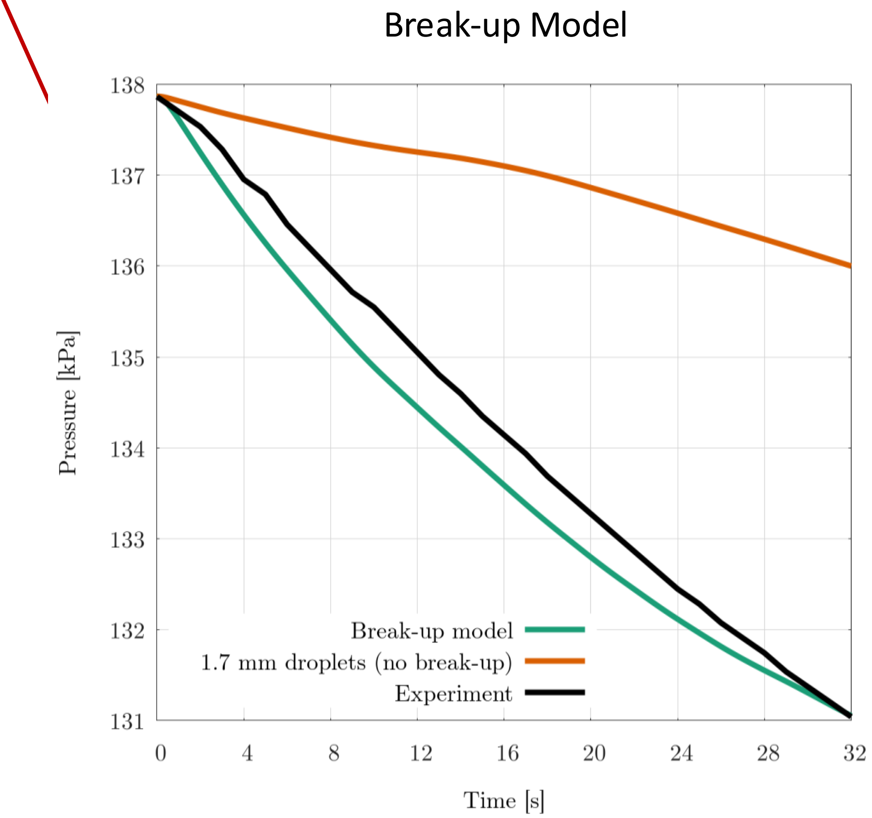

Steep thermal gradient at gas-liquid interface

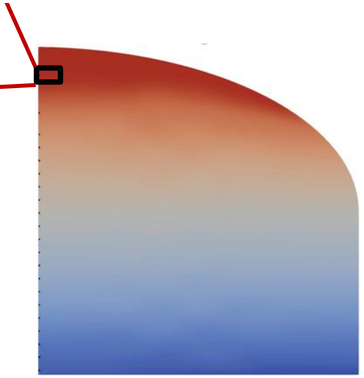
- Tank pressure is accurately predicted with very favorable rake temperature match
- Predictions are independent of modeling parameters

1e-4 m grid resolution required normal to the gas-liquid interface for accurate turbulence and thermal transport modeling

Modeling Sensitivities (1/3) – Break-up Model

Particles with injection diameter of 1.7 mm are scaled 4x for visualization
Every 100th particle is displayed

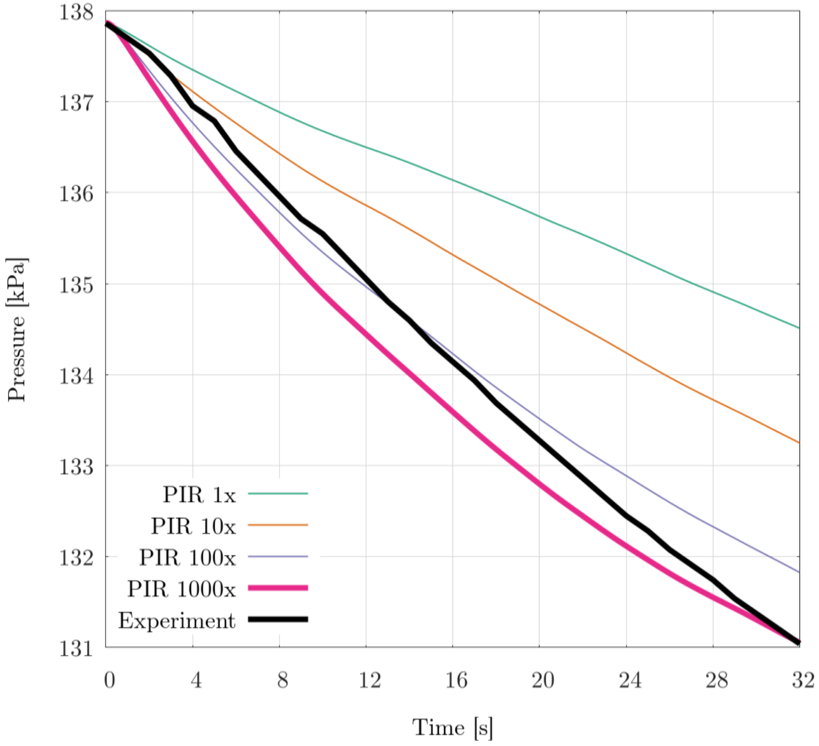

Break-up Model



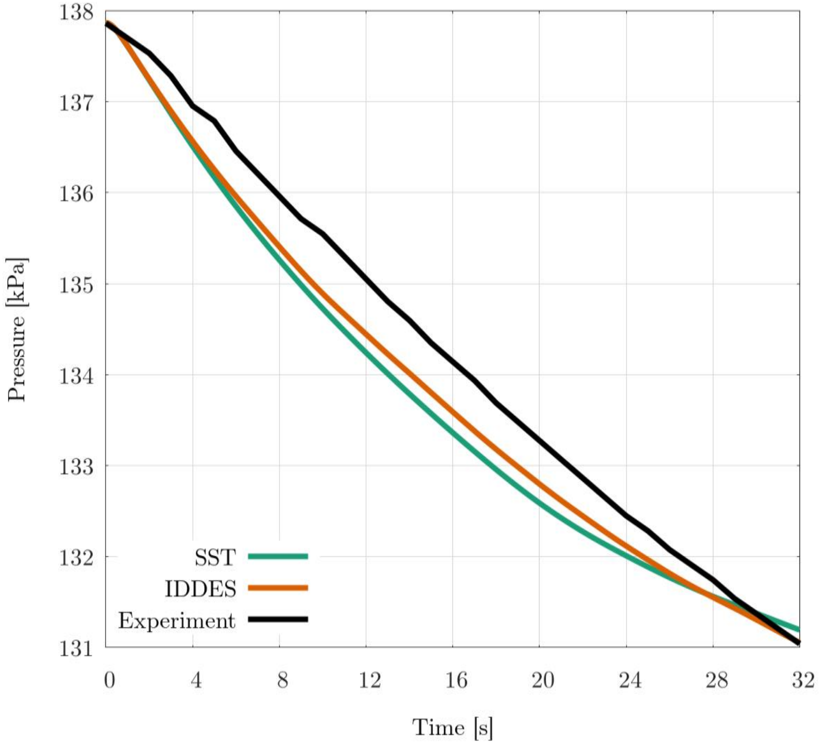
- Particle break-up and coalescence modeling ensures that spray diameter is not left to guess-work but predicted based on known flow physics
  - Depressurization rate is strongly affected by injected particle size because the change in particle surface area affects heat/mass transfer
  - Droplet sizes were not characterized for the MHTB test and are generally difficult to measure but physics-based modeling does not require a priori particle diameter information

Modeling Sensitivities (2/3)

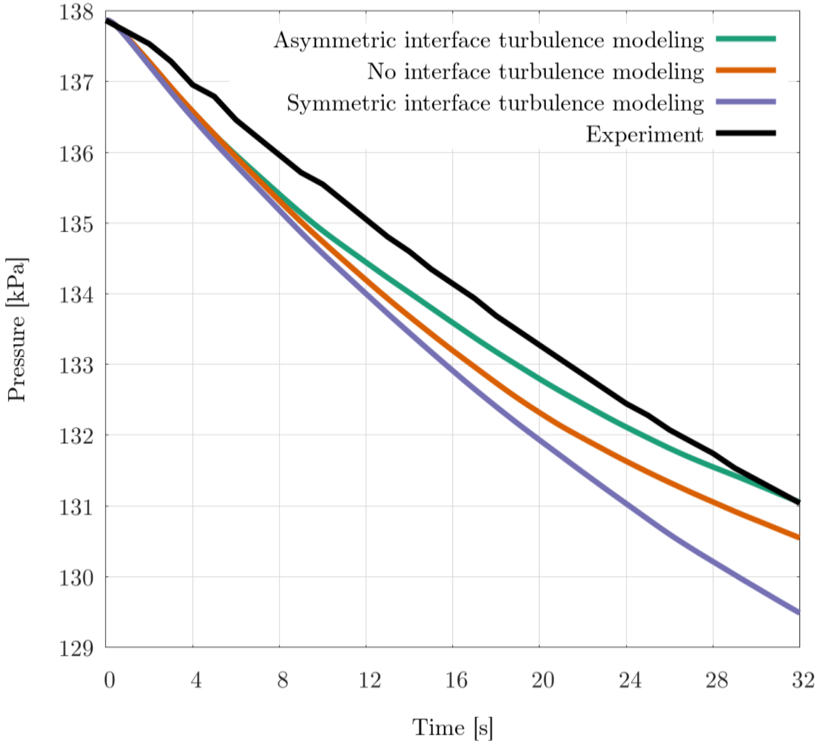
Parcel Injection Rate Sensitivity



Turbulence Modeling



Interface Turbulence Transport

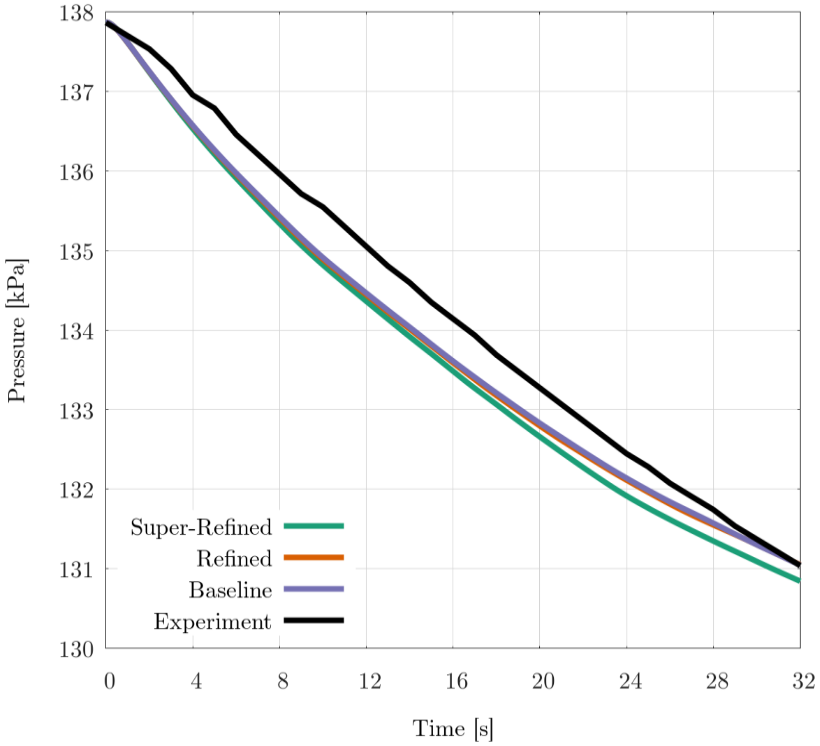


- LPT is a Monte-Carlo simulation – solution improves with more parcel injection rate, i.e., each parcel holds fewer particles
- Hybrid LES/RANS model – IDDES is slightly better at following test pressurization rate at the end of the test
- Asymmetric wall-freestream gas-liquid interface turbulence treatment produced the best comparison – consistent with experiments as well as previous validation work [1]

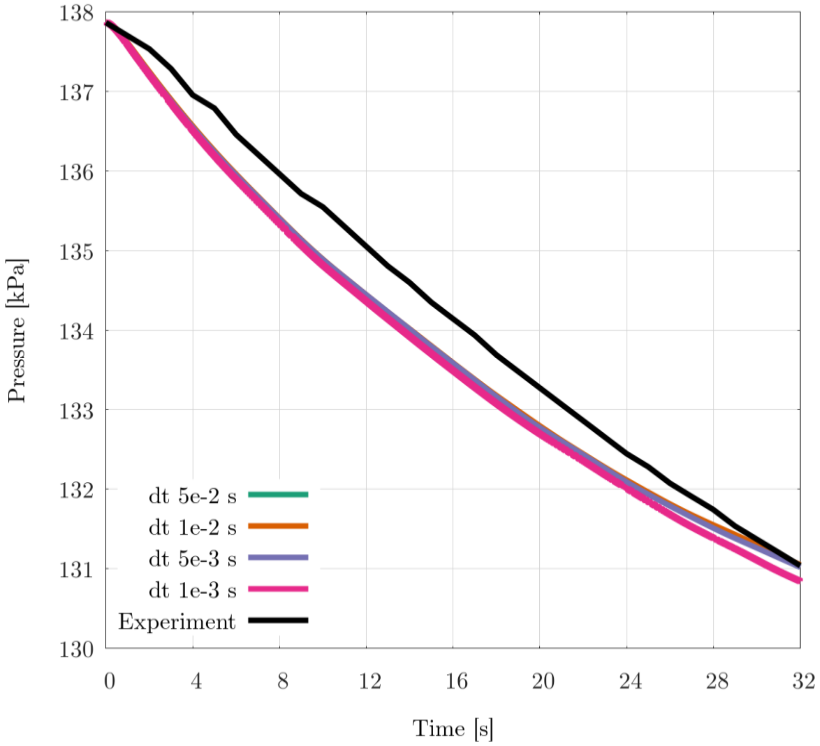
[1] Chintan Patel. "Validation of Two Phase Flow Modeling Techniques in Loci-Stream Using Axial Jet Pressure Control and Autogenous Pressurization Experiments," AIAA 2025-1358. AIAA SCITECH 2025 Forum. January 2025.

Modeling Sensitivities (3/3)

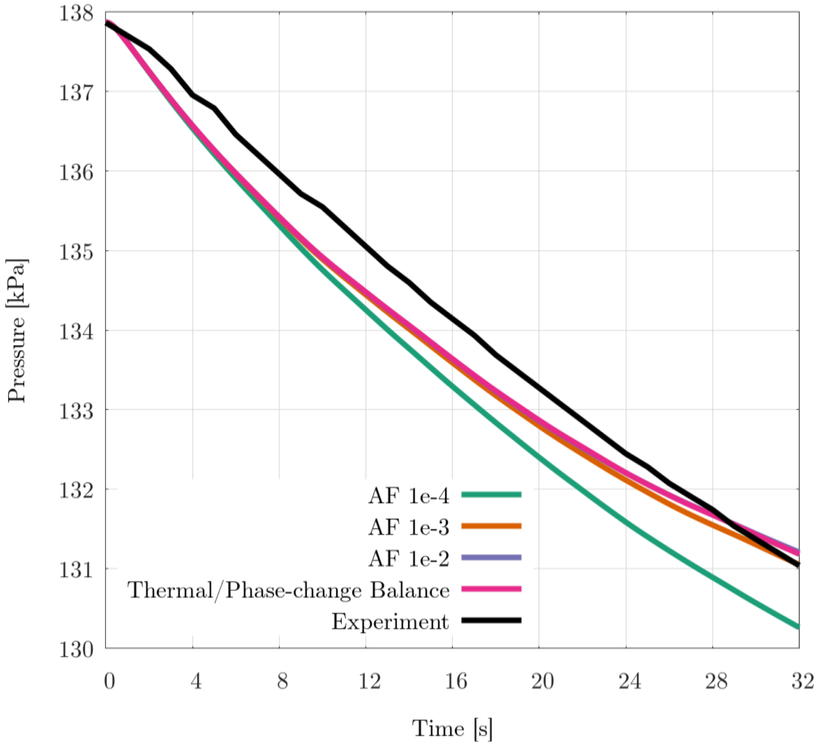
Spatial Resolution Sensitivity



Temporal Resolution Sensitivity



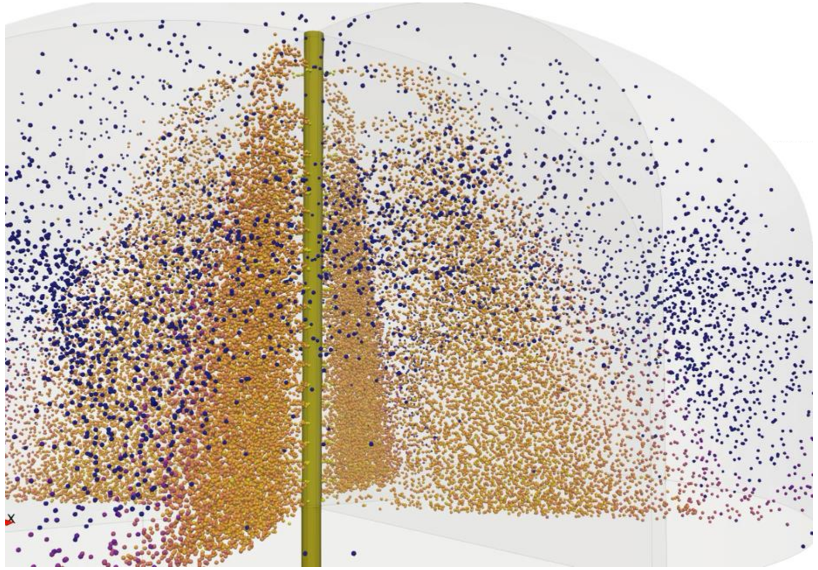
Accommodation Factor Sensitivity



- Mesh- and timestep-independent predictions
- Accommodation factor in the Eulerian phase change equation modulates the rate of evaporation/condensation. No sensitivity observed above the value of 1e-3.

Conclusion

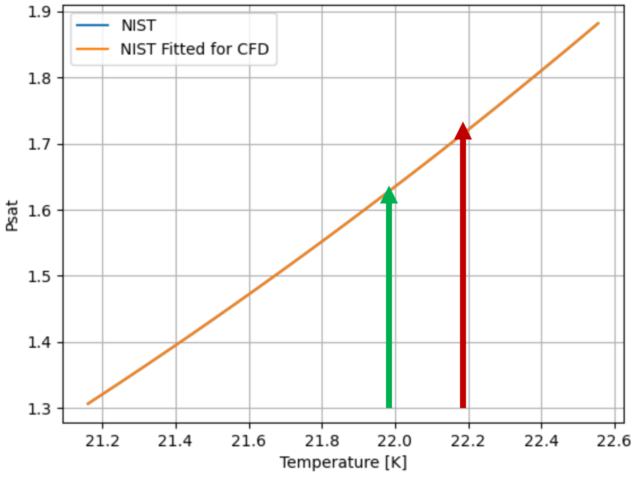
- Successfully validated Loci-Stream and Lagrangian-Eulerian multiphase flow modeling technique using MHTB tank spray-bar depressurization test
    - Weber number based Lagrangian droplet break-up and coalescence model is essential for physically accurate heat/mass transfer with Eulerian domain
    - Accurate turbulence transport is crucial for reliable modeling of spaceflight CFM operations
- The sharp interface model avoid volume of fluid method’s limitations of interface inaccuracies/instabilities and strict timestep requirement – faster simulations with more refined length/time scales
- Future work
    - Expand validation to MHTB spray-bar cooling at different fill height
    - Validate VOF method for future use with morphing interfaces
- A successful, and parameter-free validation against flight-scale tank test builds further confidence in use of Loci-Stream CFD solver and described modeling techniques for CFM modeling for human spaceflight projects.



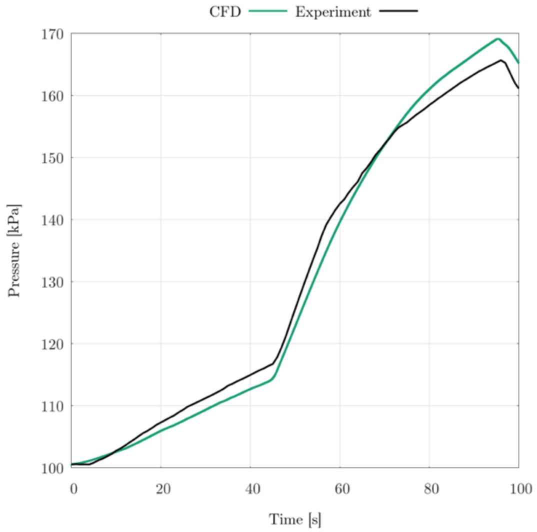
Back-up

Phase Change Model

- Saturation pressure is **very sensitive to the interface temperature**
- Phase change rate ṁ is very sensitive to the interface temperature.
    - For EDU tank autogenous pressurization experiment, 0.2 K error (1% error) in temperature results in 14% error in pressure
    - For K-site tank self-pressurization, 1 K error (5% error) in temperature results in 50% error in predicting tank pressure. For an unsteady problem, this is equivalent to being off by several hours of self-pressurization.
- Must resolve thermal gradients due to heat exchange (latent and sensible) at the interface



Parahydrogen Saturation Curve



EDU Tank Autogenous Pressurization

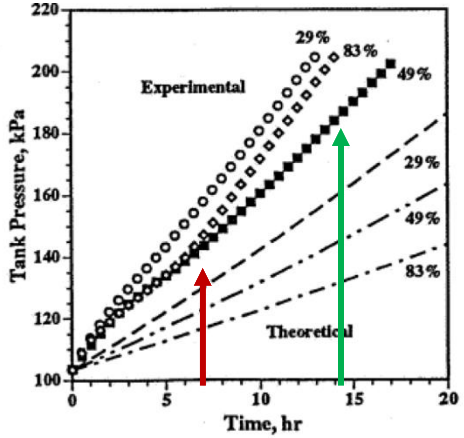
$$\dot{m} = \sqrt{\frac{1}{2\pi R_g}} \left(C_{evap} \frac{p_{sat}(T_l)}{\sqrt{T_l}} - C_{cond} \frac{p_g}{\sqrt{T_g}} \right) A_{in}$$

$$\dot{m} = C_m \sqrt{\frac{1}{2\pi R_g T_{in}}} \left(p_{sat} - p_g \right) A_{in}$$

$$log_{10}\, p_{sat} = a - \frac{b}{c + T_{sat}}$$

$$\dot{m} L = Q_l - Q_g$$

For parahydrogen, L = 4.45e6 J/kg



K-Site Tank Self-pressurization with 3.5 W/m^2 Heat Flux

Interface Turbulence Transport

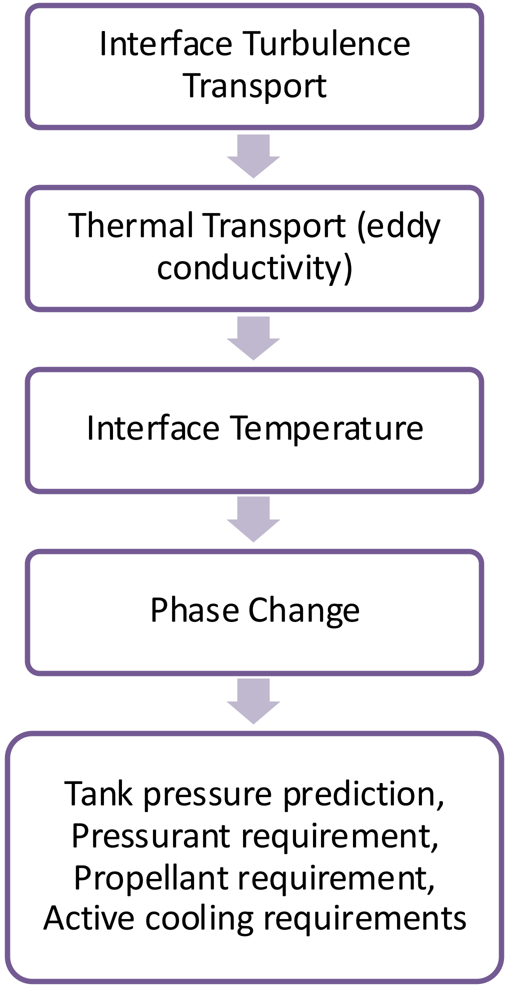
- Important physical processes
  - Phase transition
  - Interface turbulence transport (ITT)
- Reynolds-averaged Navier-Stokes (RANS) equations for mass, momentum and energy conservation
  - Turbulence Model: Menter’s Shear Stress Transport (SST) model
- Phase change model: Hertz-Knudsen-Schrage (HKS)

$$\dot{m} = \sqrt{\frac{1}{2\pi R_g}}\left(C_{evap}\frac{p_{sat}(T_l)}{\sqrt{T_l}} - C_{cond}\frac{p_g}{\sqrt{T_g}}\right)A_{in}$$

$$\dot{m} = C_m\sqrt{\frac{1}{2\pi R_g T_{in}}}\left(p_{sat} - p_g\right)A_{in}$$

$$log_{10}\, p_{sat} = a - \frac{b}{c + T_{sat}}$$

$$\dot{m}L = Q_l - Q_g$$



Interface Turbulence Transport

Thermal Transport (eddy conductivity)

Interface Temperature

Phase Change

Tank pressure prediction,
Pressurant requirement,
Propellant requirement,
Active cooling requirements

Impact of ITT on CFM

- ITT modeling heavily influences crucial design parameters of spaceflight missions
- Altered turbulence at the interface
  - RANS models have no mechanism to account for it
- CFM operations in spaceflights span days with large tanks
  - Scales for ITT and phase change processes are much smaller
- **How to make reliable predictions for flight projects?**
  - Develop models and validate them with a variety of flight-scale CFM experiments

Interface Turbulence Transport Modeling

Sharp Interface Turbulence Modeling

- Stationary/quasi-stationary gas-liquid interface modeled with a fixed interface boundary
  - Velocity and stresses continuity
- Significantly faster than volume of fluid method
  - Allows large number of numerical experiments

Modeling Evidence

- Experiments, direct numerical simulation and large eddy simulation studies demonstrate
  - Diminished turbulence kinetic energy (TKE) on the gas side of the interface
  - Either unaltered or enhanced TKE on the liquid side of the interface

Turbulence Modeling	Description	Applied to
Wall-like	Near interface modeled like a no-slip wall boundary	Gas side
Freestream-like	Turbulence unaffected by the boundary (extrapolated)	Liquid side

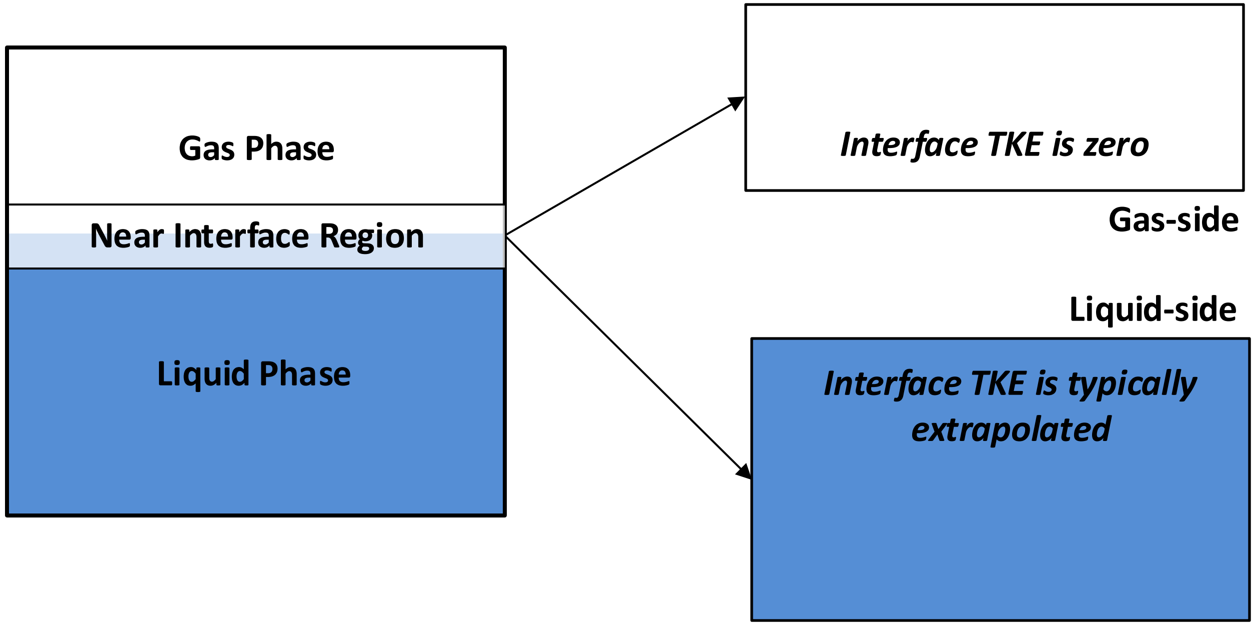


Illustration of Sharp Interface ITT Modeling Technique

Gas-Liquid Interface Turbulence Literature

- Experiments like those by Fabre et al has shown that gas side turbulence is damped at the interface ("wall-like" behavior)
  - Rashidi et al show streak formations at the interface that are similar to the wall
- DNS from Lombardi et al shows turbulence on the gas side of the interface is wall-like, i.e., damped, but the turbulence on the liquid side is enhanced.
  - For liquids, "The mean velocity distribution, turbulence intensities, Reynolds stress and various other statistical measures are significantly altered compared to those in the wall region of channel flows"
- Fulgosi et al performed DNS analysis of stratified flow and found damped turbulence on the gas side interface similar to wall sublayer, but TKE is non-zero.
  - Importantly, they observed "similarity in the distribution of the turbulence intensities near the interface". A general RANS model is plausible.
- Jofre et al studies bubbly flow using LES and found that damping on the gas side of the interface produced satisfactory comparison to DNS in the near interface region

- Summary
  - Gas-side interface turbulence: wall-like (Recall mesh requirements for heat transfer near a wall → need a low y+ mesh)
  - Liquid-side interface turbulence: either unchanged or somewhat enhanced