



Validation of Two-phase Flow Modeling Techniques in Loci-Stream using Axial Jet Pressure Control and Autogenous Pressurization Experiments

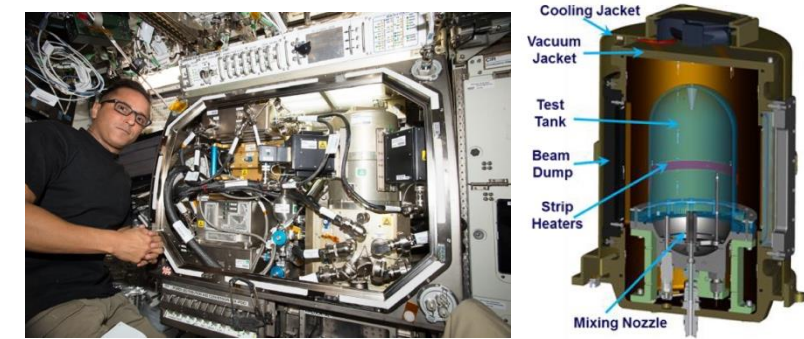
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Chintan Patel – ASEG, Fluid Dynamics Branch (NASA MSFC-ER42)

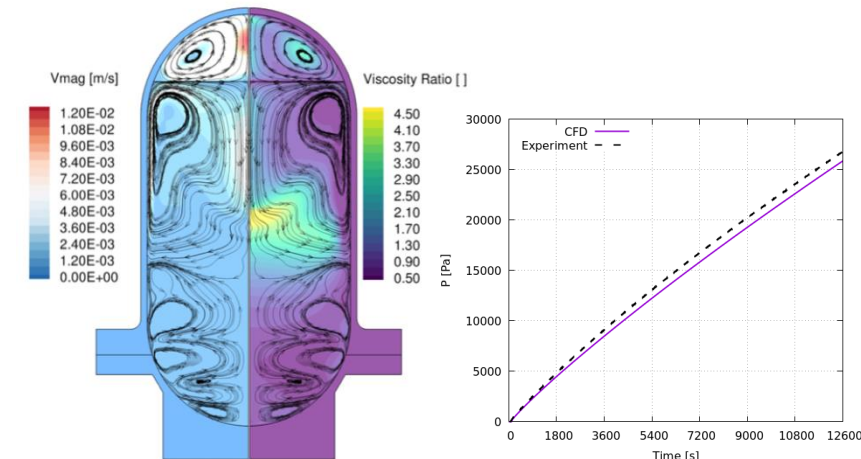
Background



- Managing cryogenics is a critical technology for NASA's Artemis missions
- Cryogenic fluid management (CFM) challenges
 - Storage and delivery: evaporative loss due to heat leakage, liquid location tracking
 - Pressure control: helium/autogenous 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



Interface Turbulence Transport

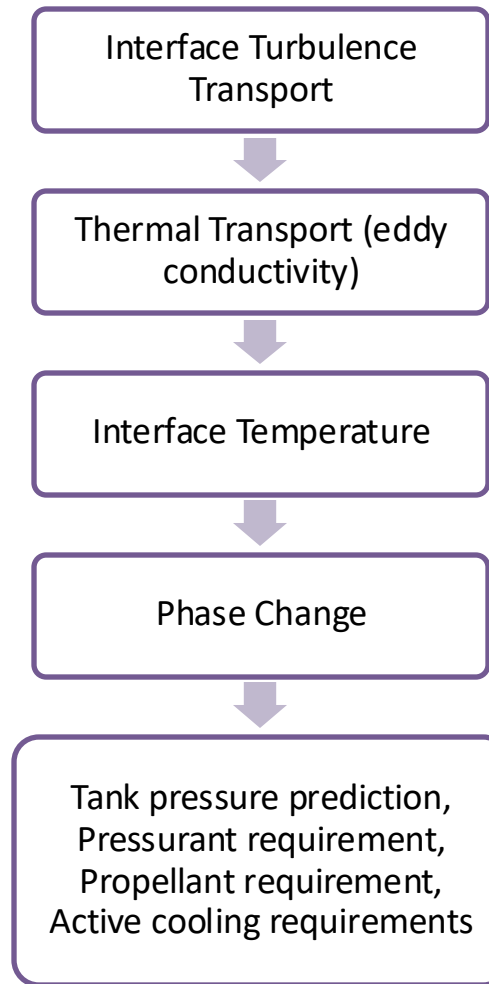
- Important physical processes
 - Phase transition
 - Interface turbulence transport (ITT)
- Reynolds-averaged Navier-Stokes (RANS) equations for mass, momentum and energy conservation
 - Turbulence Model: Menter's Shear Stress Transport (SST) model
- Phase change model: Hertz-Knudsen-Schrage (HKS)

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

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

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

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



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

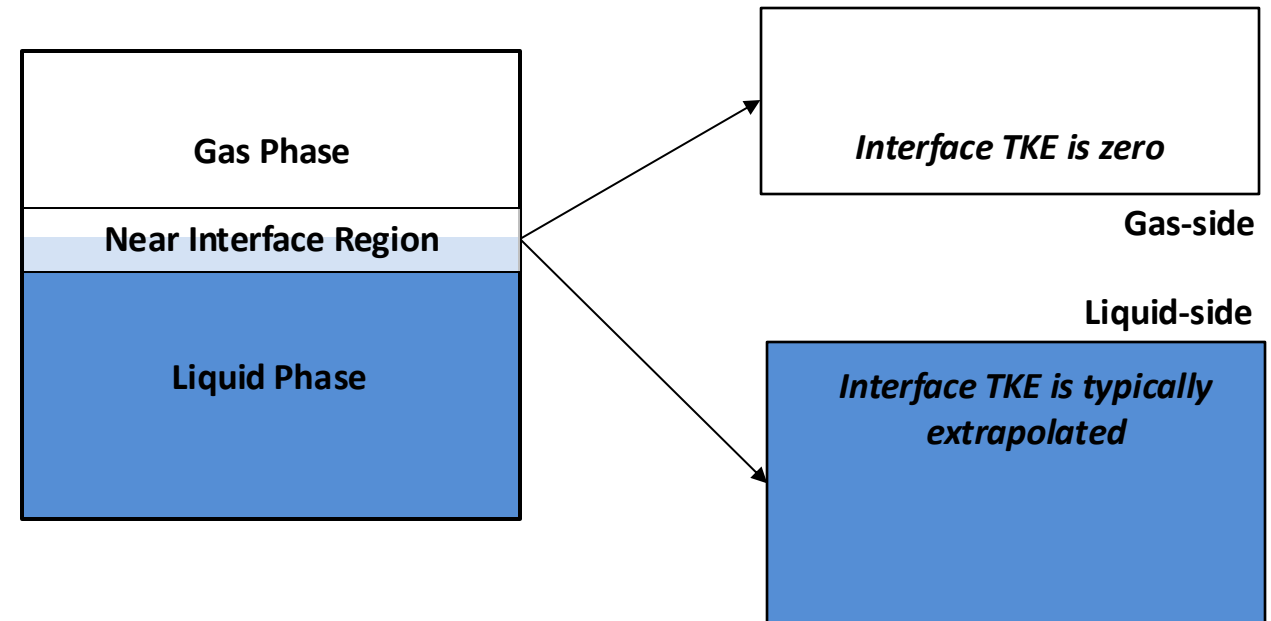


Illustration of Sharp Interface ITT Modeling Technique

1. Autogenous Pressurization Test

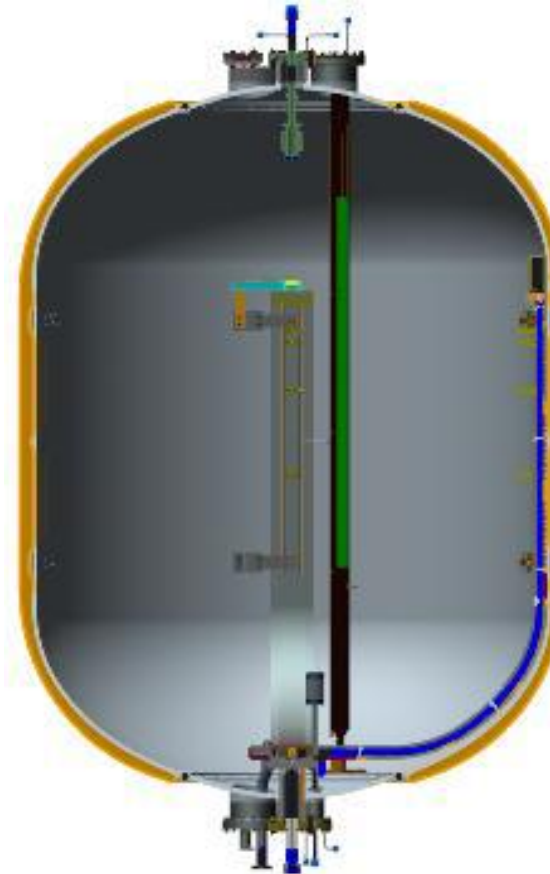
Experiment

- Performed at NASA MSFC using Engineering Design Unit tank with liquid hydrogen
- The insulated double domed tank with 1.7 m diameter was filled to 90% volume
- Uniform initial temperature of 20.345 K with saturation condition at the interface (1 bar ullage pressure)
- Pressurized with room temperature gaseous hydrogen

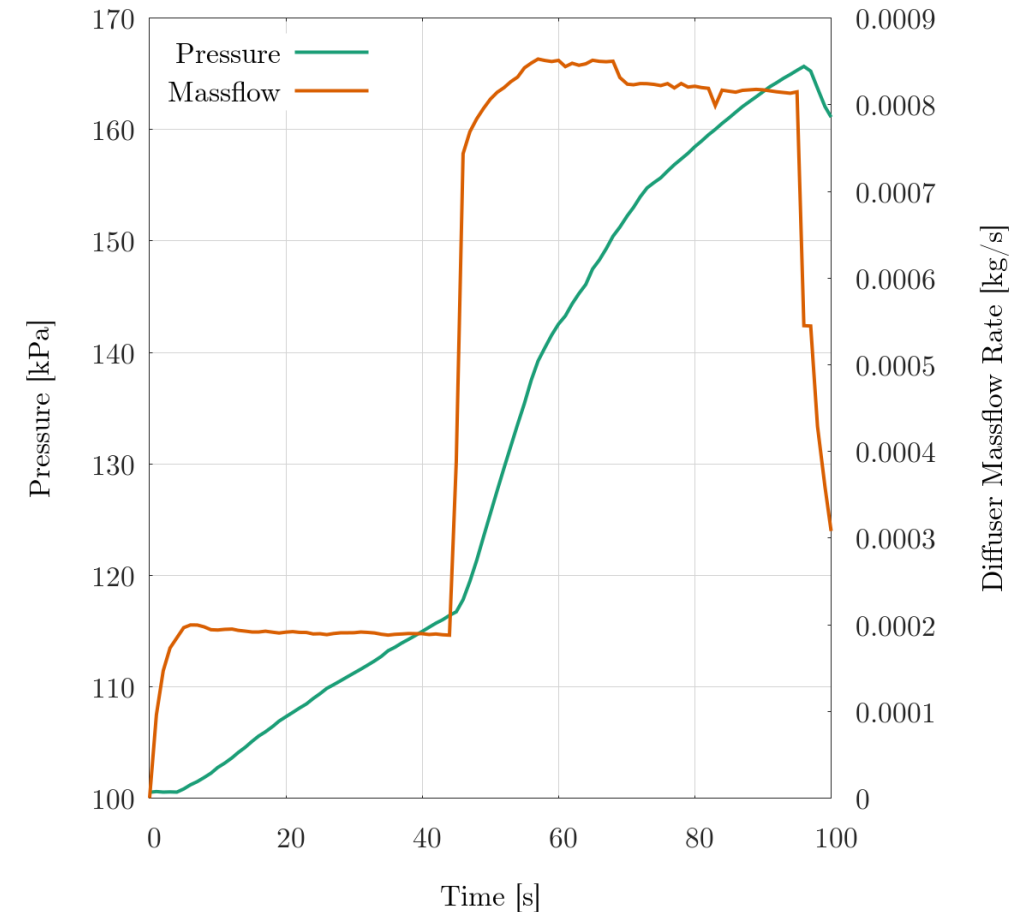
CFD Model

- Axisymmetric flow
- Conjugate heat transfer
 - Temperature dependent thermal properties for the solids

Cross Section View of the EDU Tank CAD Model



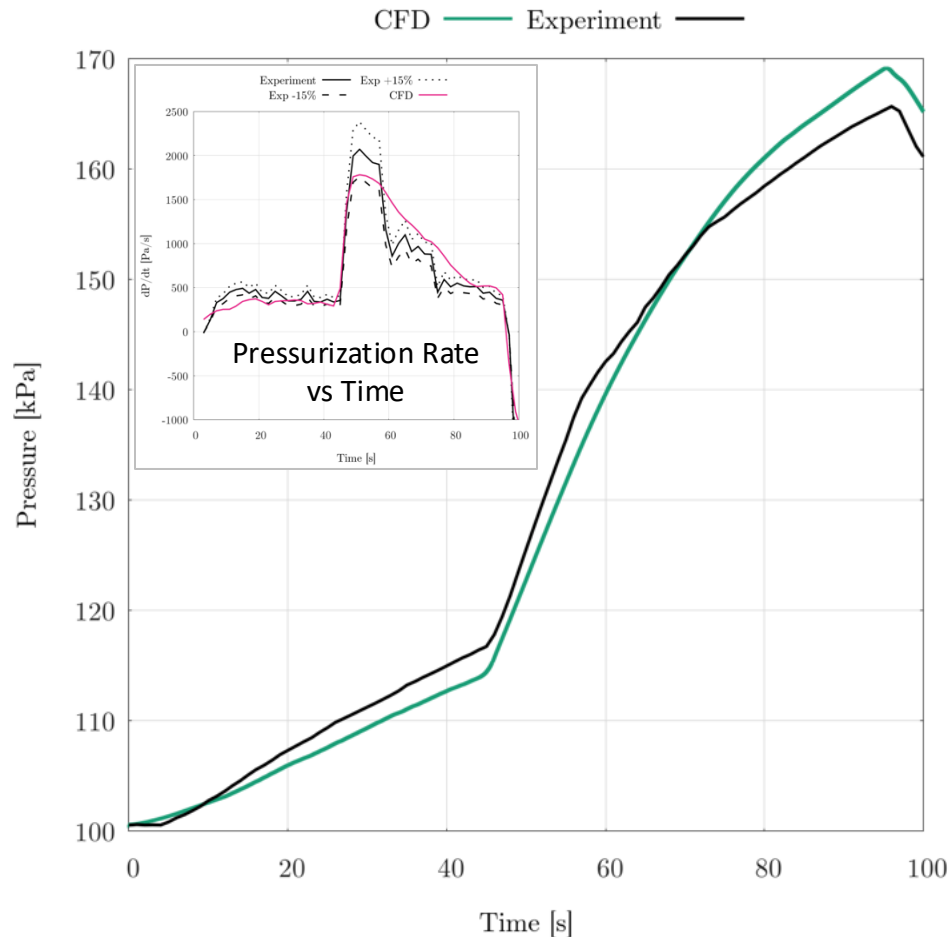
Diffuser Massflow and Tank Pressure over Time



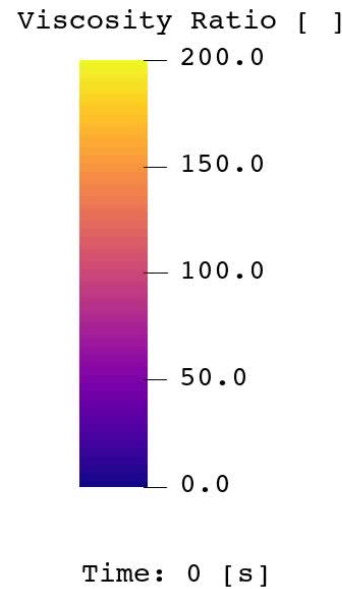


Validation – Autogenous Pressurization

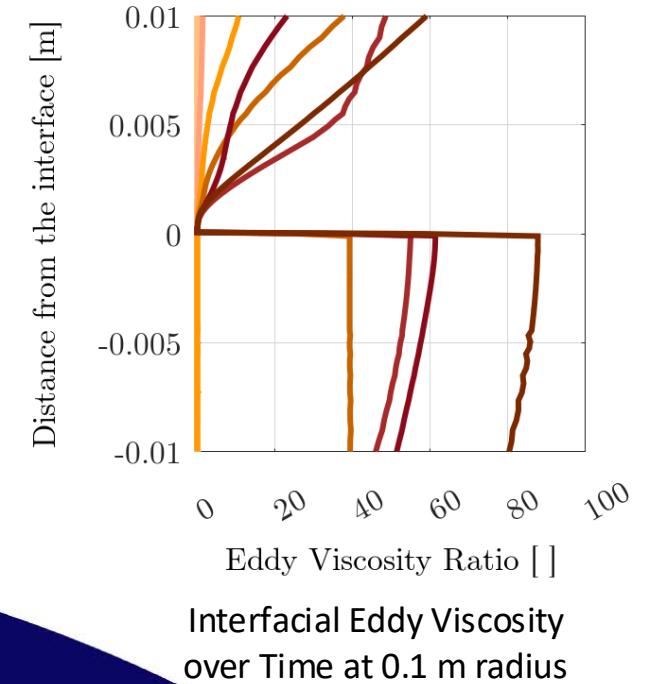
- Tank pressure was predicted successfully with 5% error
- The modeling technique allows discontinuous turbulence viscosity ratio across the interface



6 Pressure vs Time – CFD vs Experiment



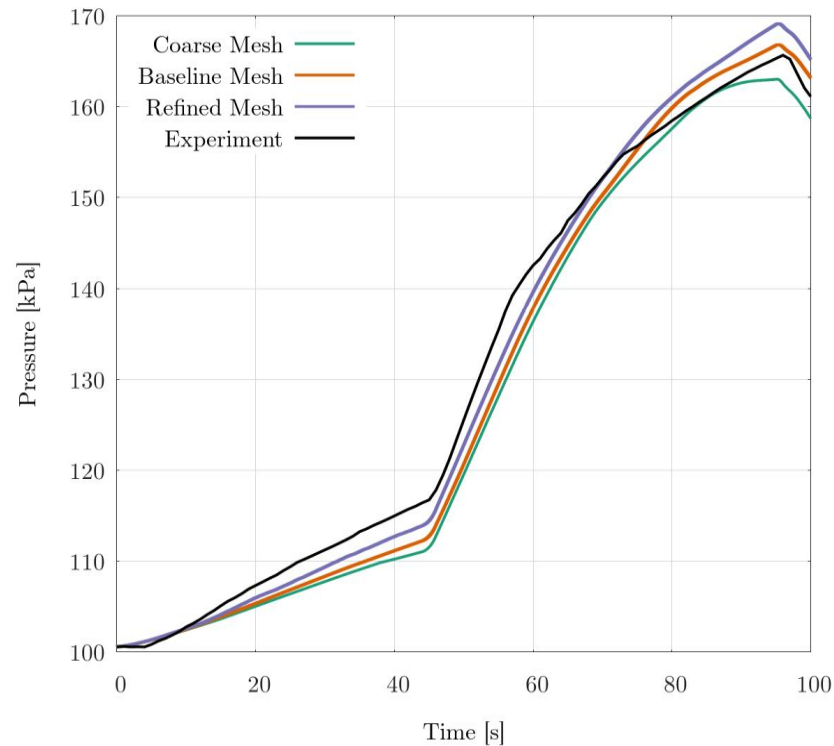
Time = 10 s — Time = 60 s —
Time = 20 s — Time = 70 s —
Time = 30 s — Time = 80 s —
Time = 40 s — Time = 90 s —
Time = 50 s — Time = 100 s —



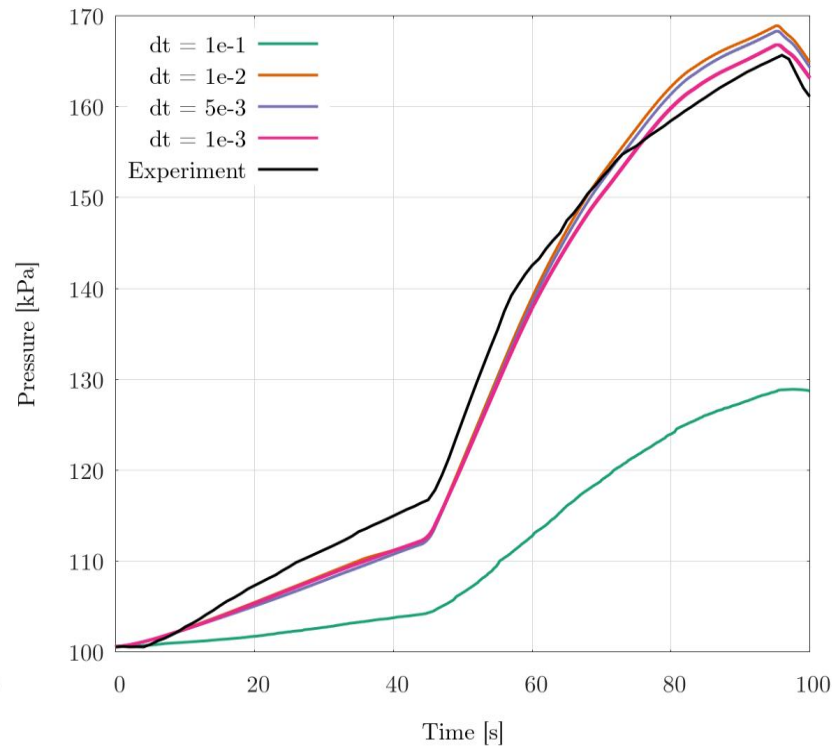
Turbulence Viscosity Ratio over Time

Validation – Autogenous Pressurization – Sensitivities

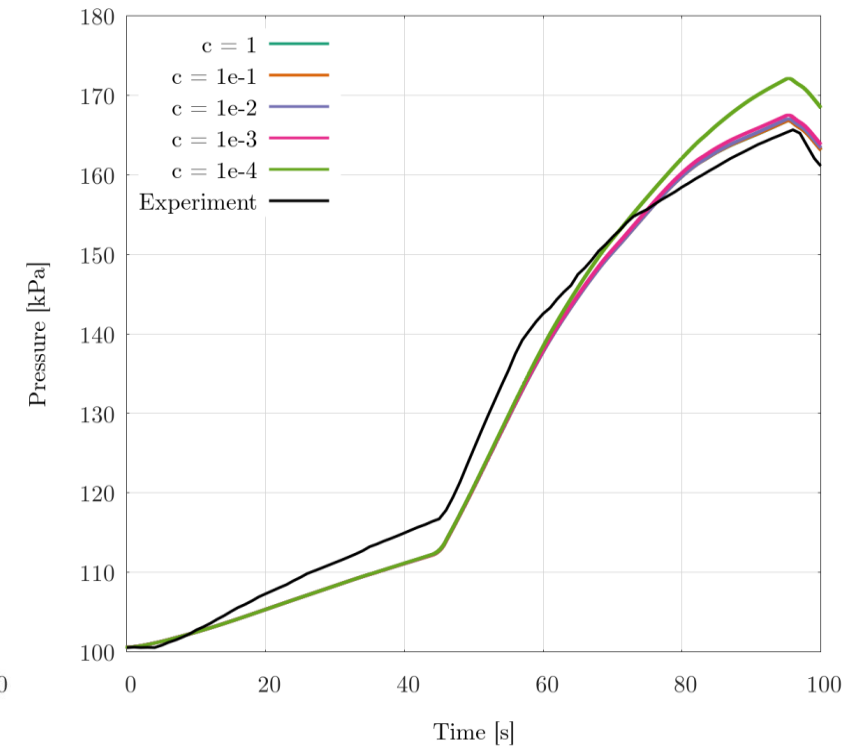
Spatial Resolution Sensitivity



Temporal Resolution Sensitivity



Accommodation Factor Sensitivity

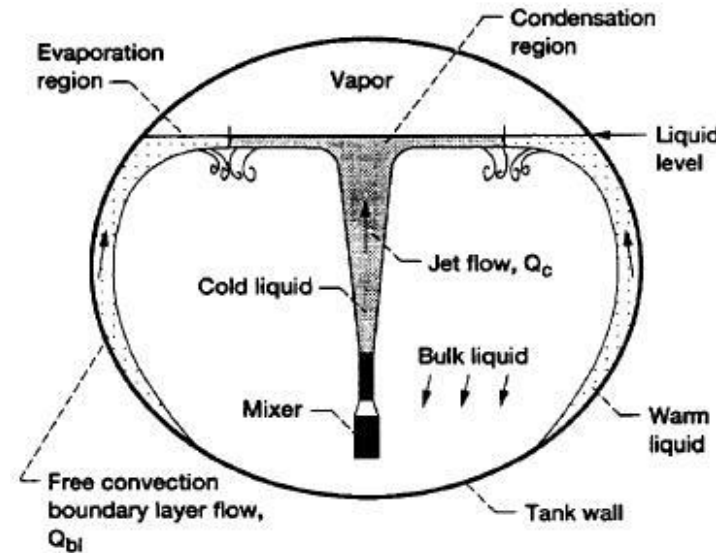


- Predictions independent of spatial and temporal resolutions are ensured
- Accommodation factor in the phase change equation modulates the rate of evaporation/condensation. Materially closed systems have shown almost no sensitivity above the value of $1e-4$. Same behavior is observed here above the value of $1e-3$.

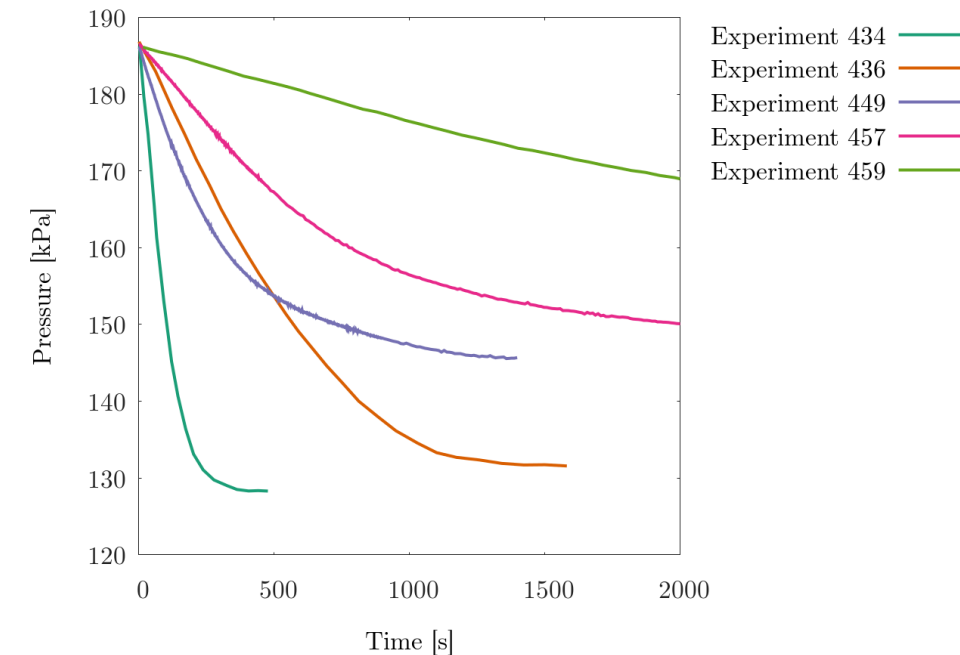
2. Axial Jet Pressure Control Test

Experiment

- Performed at NASA Glenn Research Center's (GRC) K-site facility with liquid hydrogen
- The ellipsoidal tank with 2.2 m diameter in a vacuum chamber
 - A mixer recirculates cold liquid to reduce tank pressure
- Five tests – two fill levels and three mixer massflow rates



K-site Tank Schematic^[1]



Tank Pressure vs Time

CFD Model and Solution

- Axisymmetric flow
- Predictions are independent of timestep, grid, and HKS accommodation factor

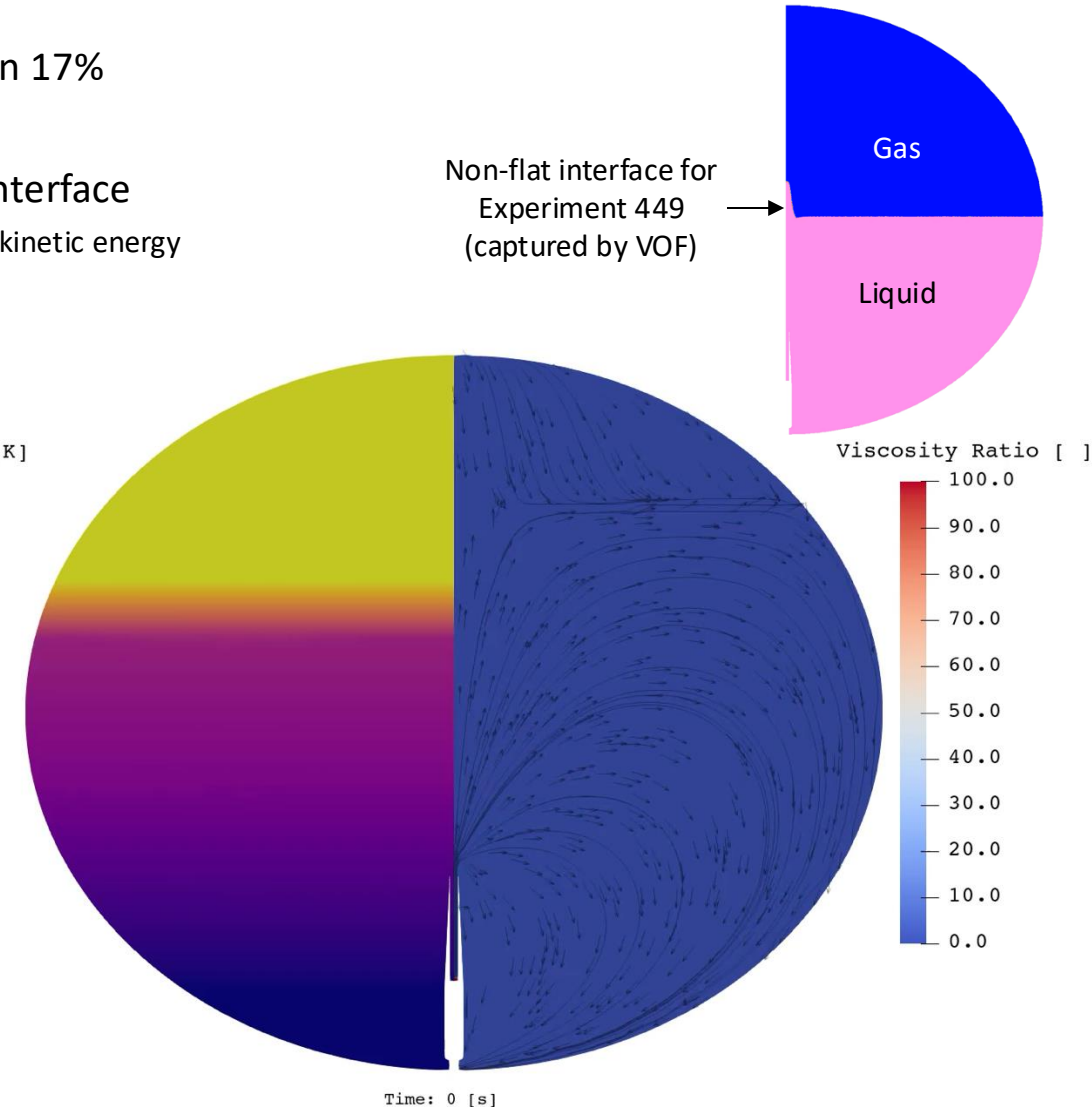
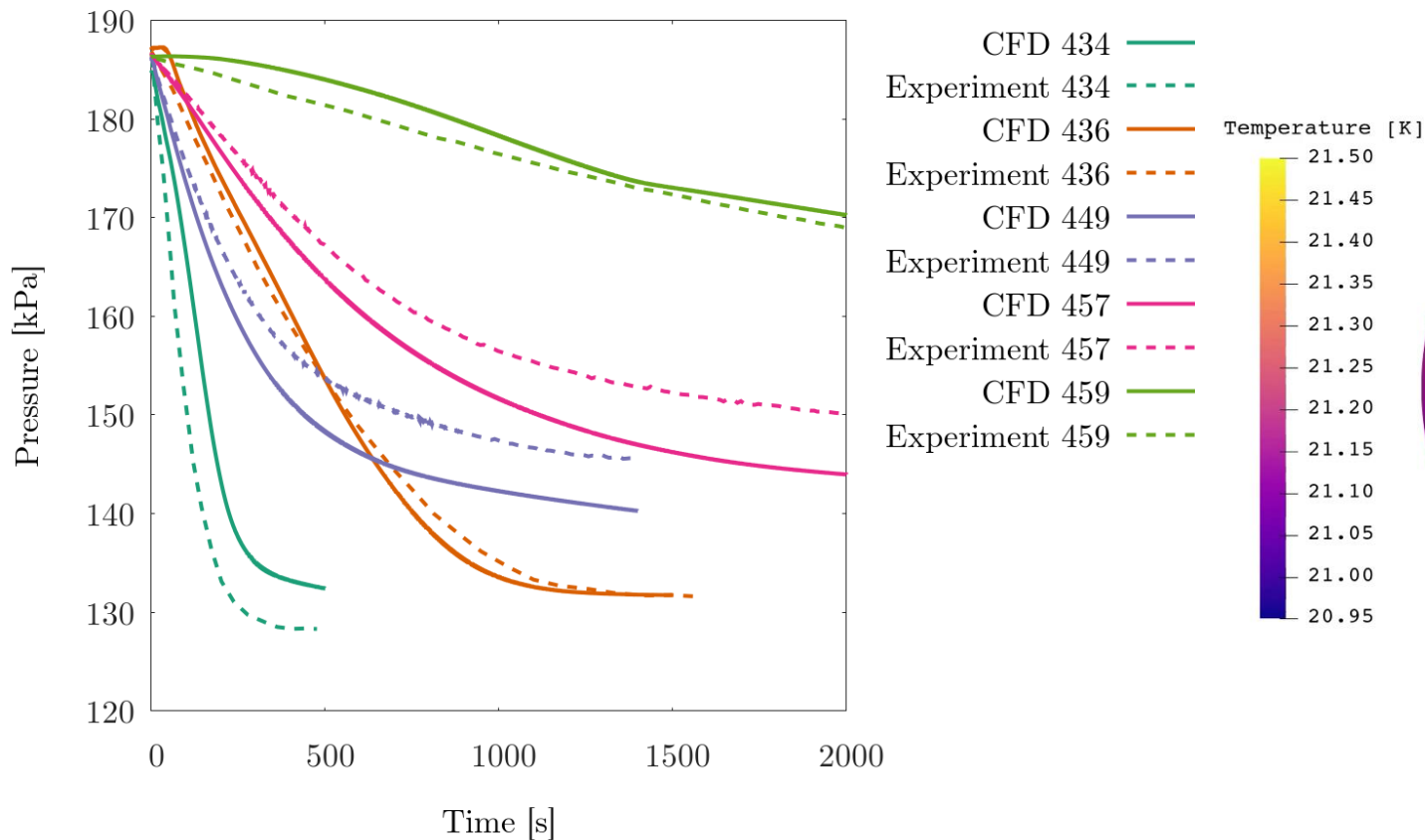
Case	Fill Volume [%]	Fill Height [m]	Mixer Flow Rate [m^3/hr]	Initial Tank Pressure [bar]
434	86.3	1.45 (79.1%)	3.47	1.861
436	85.3	1.43 (78.0%)	1.82	1.870
449	49.1	0.93 (50.7%)	3.41	1.861
457	49.1	0.93 (50.7%)	1.82	1.865
459	49.1	0.93 (50.7%)	0.92	1.847

Test Conditions

Validation – Axial Jet Pressure Control



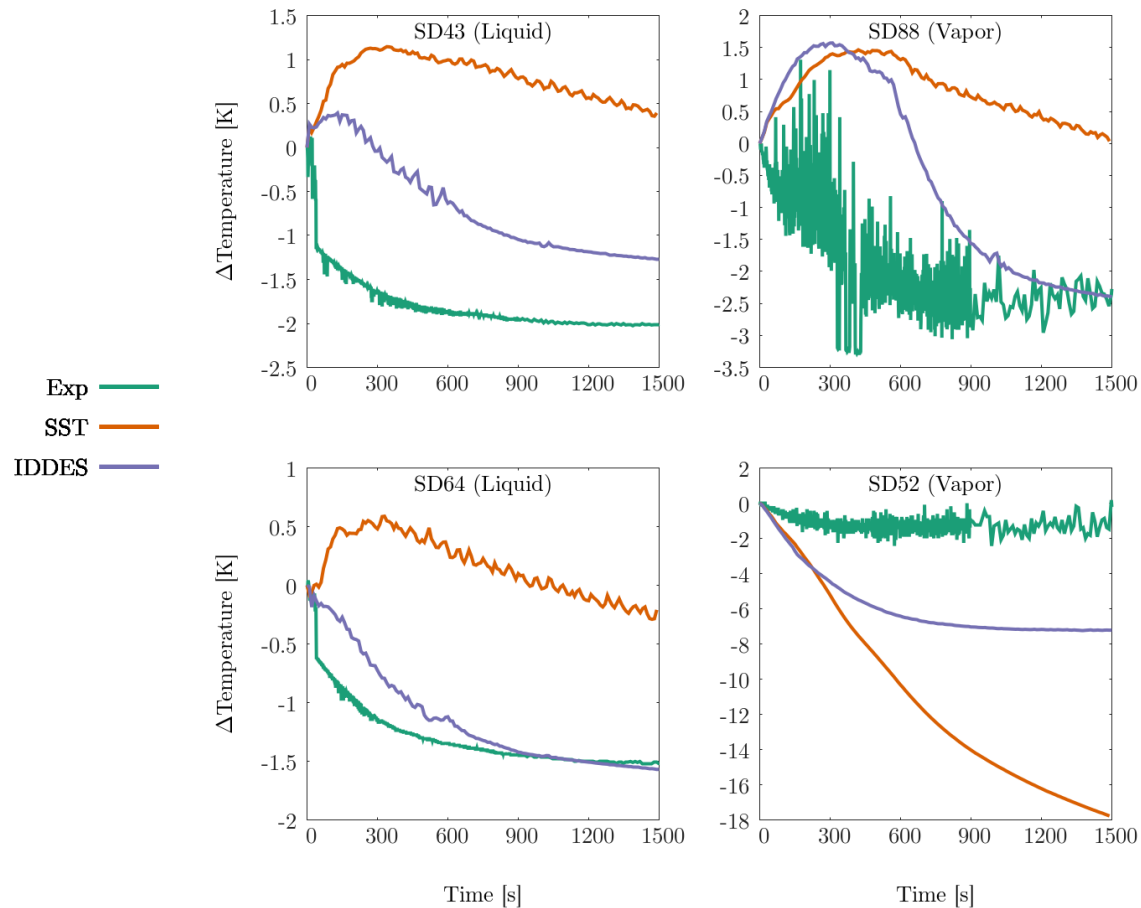
- Successful validation – Maximum pressure prediction error was less than 17%
- Wall-like interface turbulence modeling was used on both sides of the interface
 - Counterbalance overprediction due to flat interface assumption by lowering turbulence kinetic energy



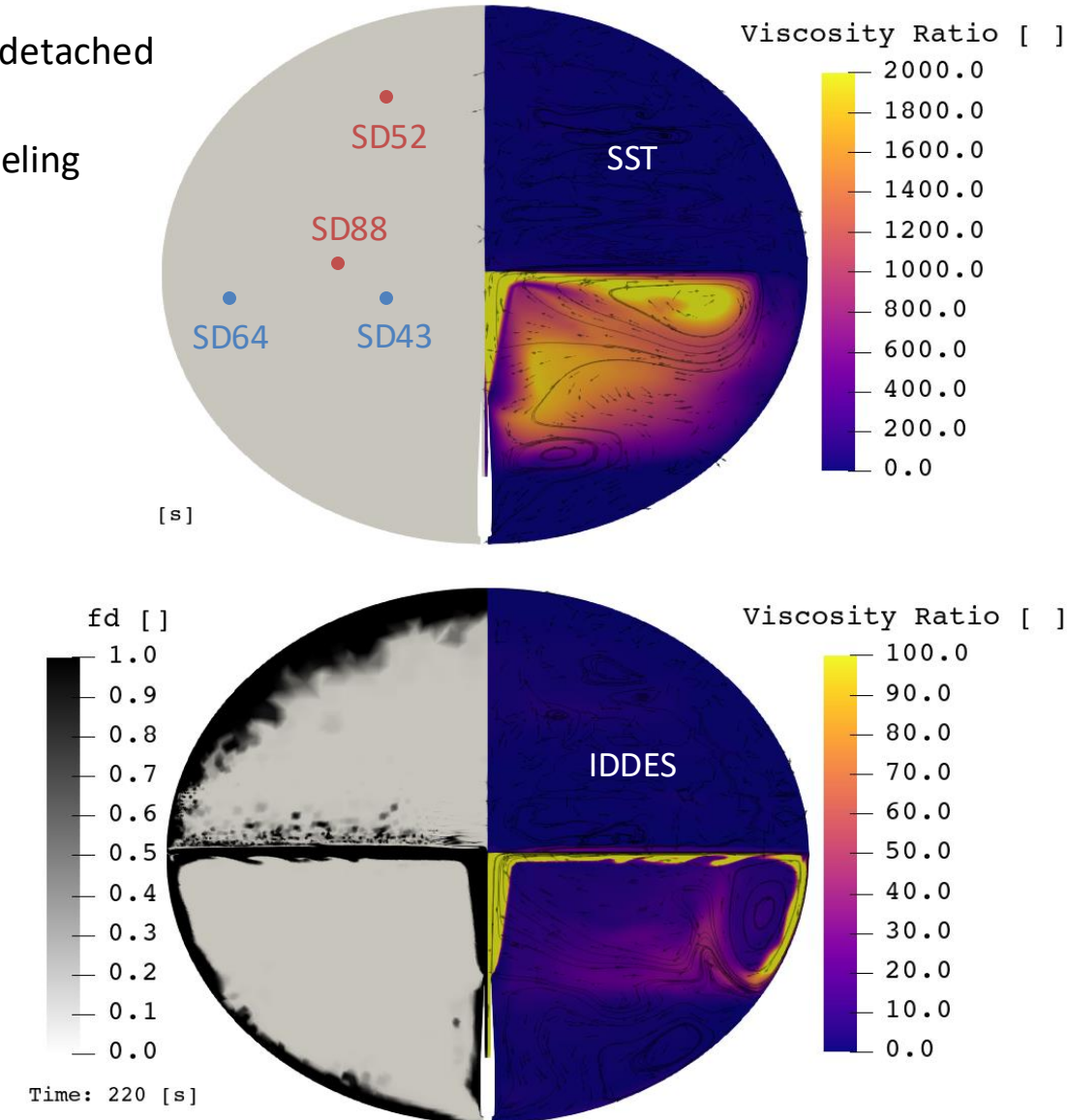
Temperature and Viscosity Ratio over Time (Exp 434)

Axial Jet Pressure Control – Temperature and Turbulence (1/2)

- RANS temperature prediction is improved by IDDES (Improved delayed detached eddy simulations) modeling of turbulence
- IDDES inhibits non-physical turbulence transport seen in the RANS modeling



Temperature probe comparison (Exp 449)

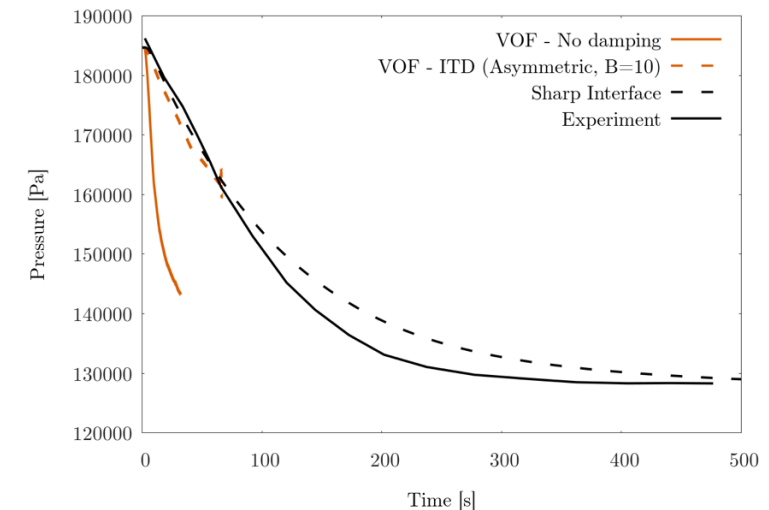


SST vs IDDES Turbulence Viscosity Ratio (Exp 449, time: 220 s)



Conclusion

- Successfully validated Loci-Stream and the interface turbulence transport (ITT) modeling technique using autogenous pressurization and axial jet-based depressurization tests
 - ITT is crucial for reliable modeling of spaceflight CFM operations
- The sharp interface model with simple ITT modeling is significantly faster than volume of fluid method and allows resolution of smaller scales
- Demonstrated improved temperature predictions (and turbulence transport) compared to the RANS turbulence modeling using IDDES
- Future work
 - Continuing to expand the validation to more CFM operations
 - Developing ITT model for volume of fluid method to simulate morphing interfaces
- Validation against flight-scale tank experiments builds further confidence in reliability of our CFD tools for a wider range of CFM applications for supporting design/analysis of the long-term space flight missions
 - Insights gained from the validations are helping in-line support of Human Landing System spaceflight projects



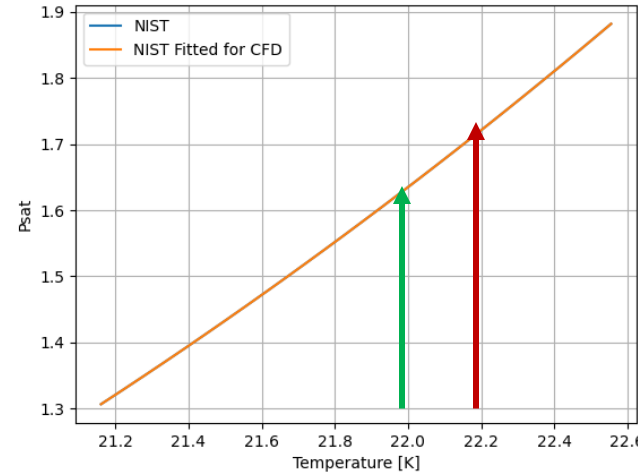
Improved Pressure Prediction
using VOF with Interface
Turbulence Damping



Back-up

Phase Change Model

- Saturation pressure is **very sensitive to the interface temperature**
- Phase change rate $\dot{m}$ 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

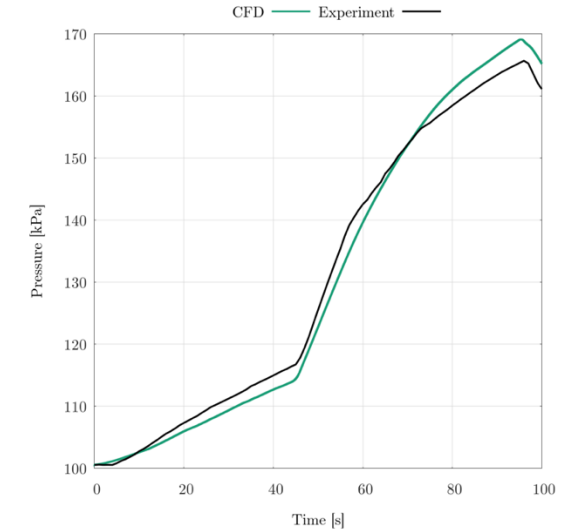
$$\dot{m} = \sqrt{\frac{1}{2\pi R_g}} \left(C_{evap} \frac{p_{sat}(T_l)}{\sqrt{T_l}} - C_{cond} \frac{p_g}{\sqrt{T_g}} \right) A_{in}$$

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

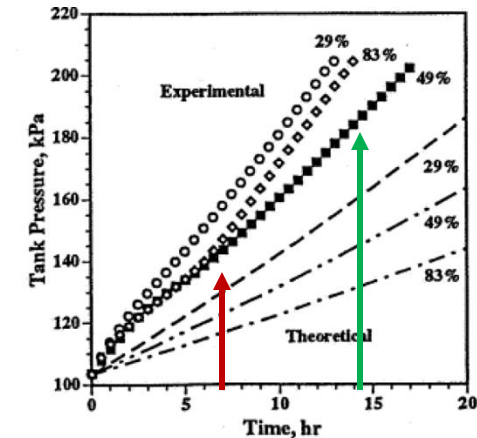
$$\log_{10} p_{sat} = a - \frac{b}{c + T_{sat}}$$

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

For parahydrogen, $L = 4.45 \times 10^6$ J/kg



EDU Tank Autogenous Pressurization



K-Site Tank Self-pressurization with 3.5 W/m² Heat Flux

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