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Effect of Interfacial Turbulence and Accommodation Coefficient on CFD Predictions of Pressurization and Pressure Control in Cryogenic Storage Tank

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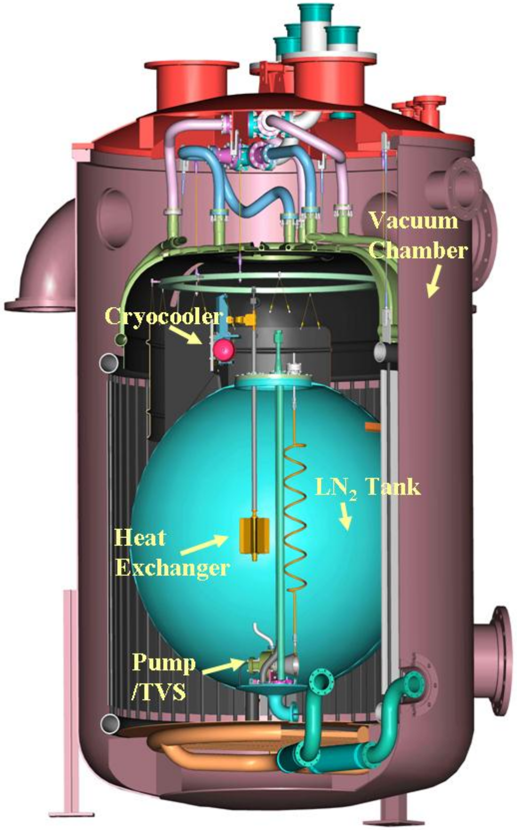
Background

- NASA has identified cryogenic storage & transfer as an area with greatest potential for cost saving
- Zero-Boil-Off (ZBO)or Reduced Boil-Off (RBO) dynamic storage tank pressure control that involves some mode of mixing of the bulk liquid with or without active or passive cooling is needed to realize cost savings.
- Optimization of ZBO or RBF tank design for microgravity applications will most probably be accomplished with only ground-testing due to budgetary constraint.
- State-of-the-Art validated storage tank CFD models will play an crucial role in extrapolation of the 1g tested storage tank design to microgravity and partial gravity applications.



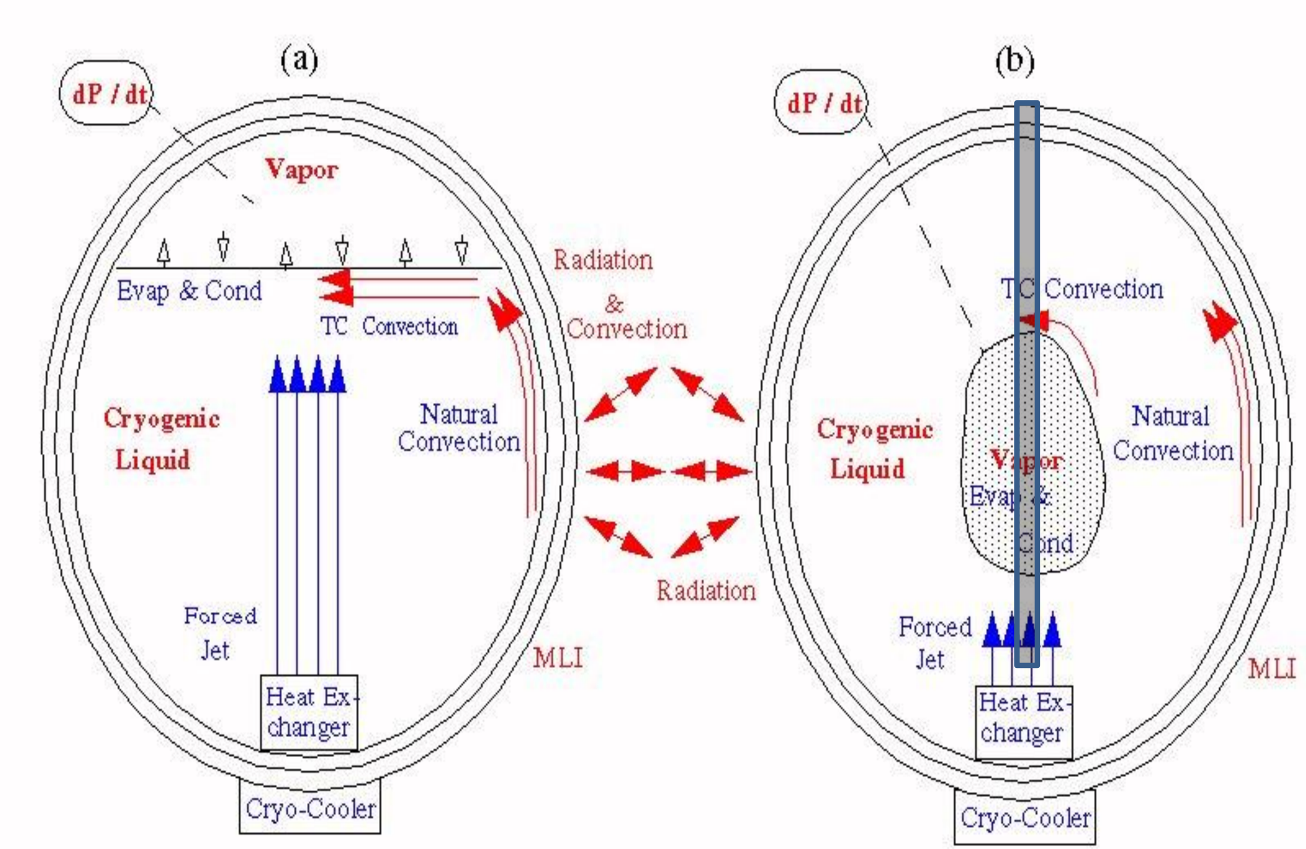
- Correct implementation of Interfacial & bulk turbulence and evaporative condensing mass transfer is crucial for the fidelity and validity of the CFD models.

Fundamental Multiphase Science Issues

- *Natural Convect (turbulence)*
- *Forced Mixing (turbulence)*
- *Evaporation Condensation*
- Microgravity Superheats

- Non-Condensable Gases
- Transport Barrier
- Marangoni Convection
- Interfacial Kinetics

- Free Surface Dynamics
- Contact Angle Dynamics
- Sloshing/Droplet Transport
- Phase Control/Positioning



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Two-Phase Sharp Interface Storage Tank CFD Model

Equation	Liquid	Ullage
Continuity	√	√
Navier Stokes	√	√
Energy	√	√
Turbulence (k-ω SST)	√	√

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0$$

Momentum:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v} \vec{v}) = -\nabla p + \nabla\left[\mu_{eff}\left(\nabla \vec{v} + \nabla v^{T}\right)\right] + \rho \vec{g} + \vec{F}_{vol}$$

Energy:

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = \nabla\left(k_{eff} \nabla T\right) + S_h$$

Interfacial Energy Balance:

$$L J_v = -k_l \vec{\nabla} T_l \cdot \hat{n} + k \cdot \vec{\nabla} T \cdot \hat{n} \quad \surd$$

$$T_I = T_{sat}(P_v)$$

Schrage Interfacial Mass Transfer:

$$J_v = \frac{2\sigma}{2-\sigma} \frac{1}{\sqrt{2\pi R T_I}} \left[P_{sat}(T_I) - P_v\right] \quad \surd$$

$$\frac{P_{sat}(T_I)}{P_r} = e^{\left[\frac{L}{R}\left(\frac{1}{T_r} - \frac{1}{T_I}\right)\right]} \quad \surd$$

Two-Phase VOF Storage Tank CFD Model

Continuity:

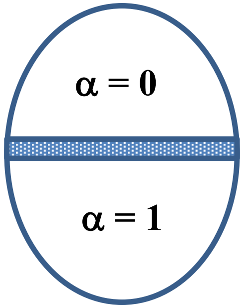
$$\frac{\partial \rho}{\partial t} + \nabla(\rho\vec{v}) = 0$$

Momentum:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\left[\mu_{eff}\left(\nabla\vec{v} + \nabla v^{T}\right)\right] + \rho\vec{g} + \vec{F}_{vol}$$

Energy:

$$\frac{\partial}{\partial t}(\rho E) + \nabla\left(\vec{v}(\rho E + p)\right) = \nabla\left(k_{eff}\nabla T\right) + S_h$$



Volume of Fluid (VOF) model:

Energy and Temperature are defined as mass average scalars:

$$E = \frac{\sum_{q=1}^{2} \alpha_q \rho_q E_q}{\sum_{q=1}^{2} \alpha_q \rho_q}$$

Properties:

$$\rho = \sum_{q=1}^{2} \alpha_q \rho_q, \quad \mu_{eff} = \sum_{q=1}^{2} \alpha_q \mu_{eff\ q}, \quad k_{eff} = \sum_{q=1}^{2} \alpha_q k_{eff\ q}$$

Continuity of Volume Fraction of the *q*-th phase:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla\cdot\left(\alpha_q \rho_q \vec{v}_q\right) = S_{\alpha_q}\right]$$

Interfacial mass transfer per unit volume:

$$S_{\alpha_q} = \dot{\mathbf{m}}_i \cdot \mathbf{A}_{i,} \left[\frac{kg}{m^3 \cdot \sec}\right]$$

$\mathbf{A}_i = |\nabla\alpha|$, is an interfacial area density in 1/m, $\dot{\mathbf{m}}_i$ is a mass flux vector in kg/(m²·sec).

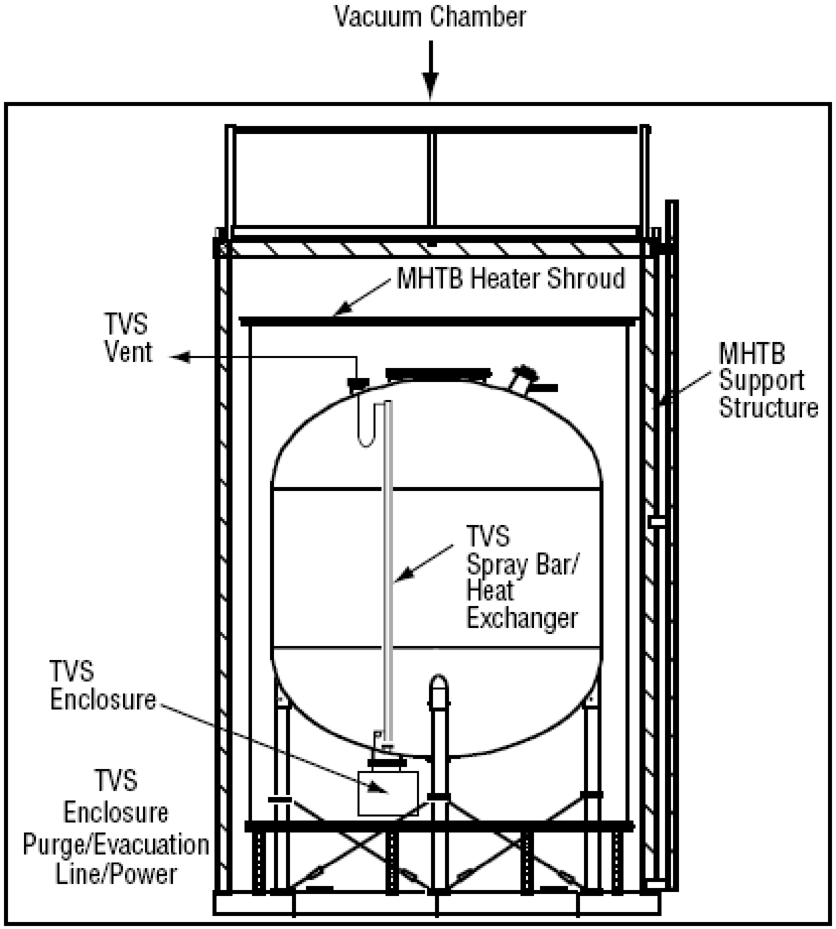
where α is a volume fraction of the primary phase

Schrage's Relation :

$$|\dot{\mathbf{m}}| = \left(\frac{2\sigma}{2-\sigma}\right)\left(\frac{M}{2\pi R}\right)^{1/2}\left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}}\right), \left[\frac{kg}{m^2 \cdot \sec}\right] \qquad (4)$$

MHTB Facility (1996-2005)

- Self-pressurization tests were run with **LH2**
- Cylindrical midsection with:
  - **height = 3.05 m**
  - **diameter = 3.05 m**
- Ullage pressure, 2 Fluid temperature rakes, Large number of Wall Temperature measurements
- Boil-off test was performed prior to tank lockup and self-pressurization
- Most tests include 20, **50, 90%** fill levels
- Heat Flux = **2.05 W/m^2**
- Tank Internal volume 37.5 m^3
- 2:1 elliptical top and bottom domes
- Tank is enclosed in a vacuum shroud.



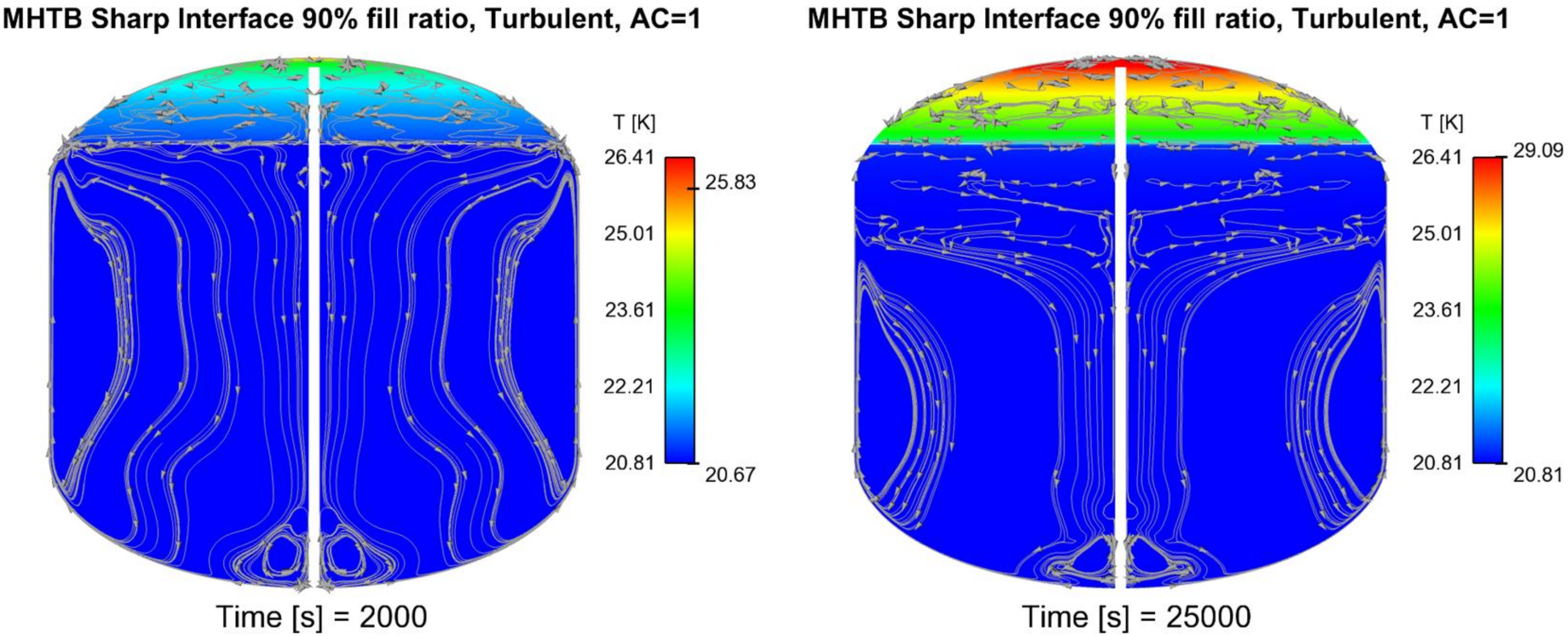
Multi-purpose Hydrogen Test Bed (MHTB) at NASA Marshall Space Flight Center

Effect of Accomodation Coefficient

MHTB Pressurization – MHTB 90%

Sharp Interface Model

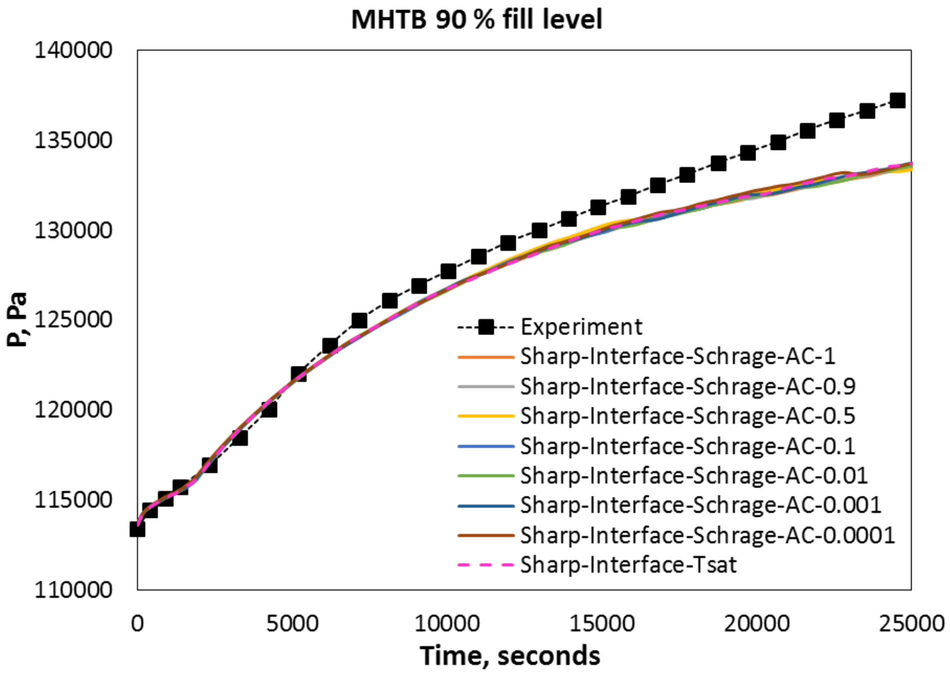
Heat Flux = 2.05 W/m^2

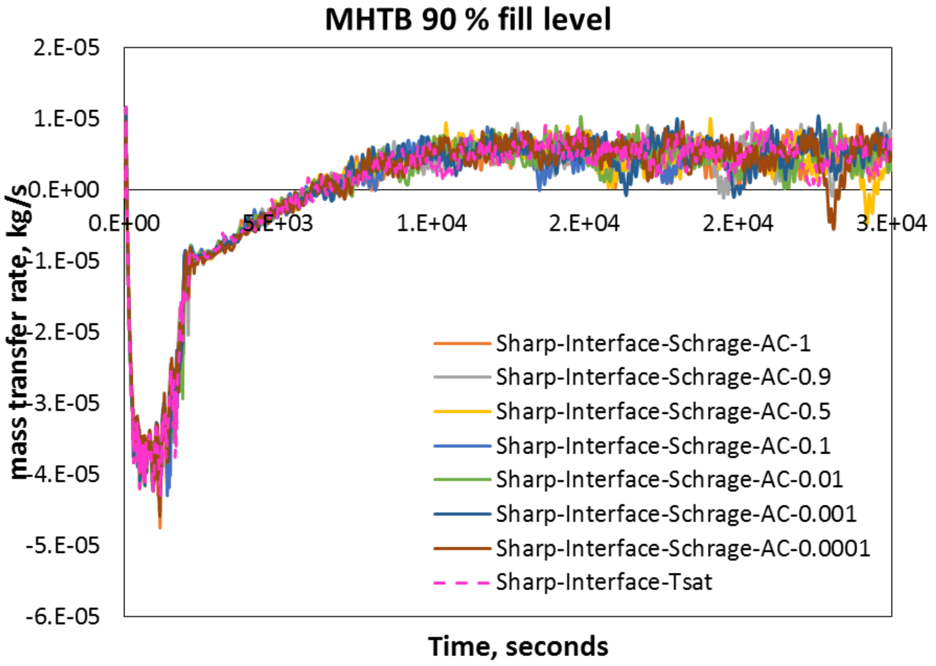


Effect of Accommodation Coefficient – MHTB 90%
Sharp Interface Model

MHTB 90% Self-Press with Sharp Interface - Schrage model

Heat Flux = 2.05 W/m^2



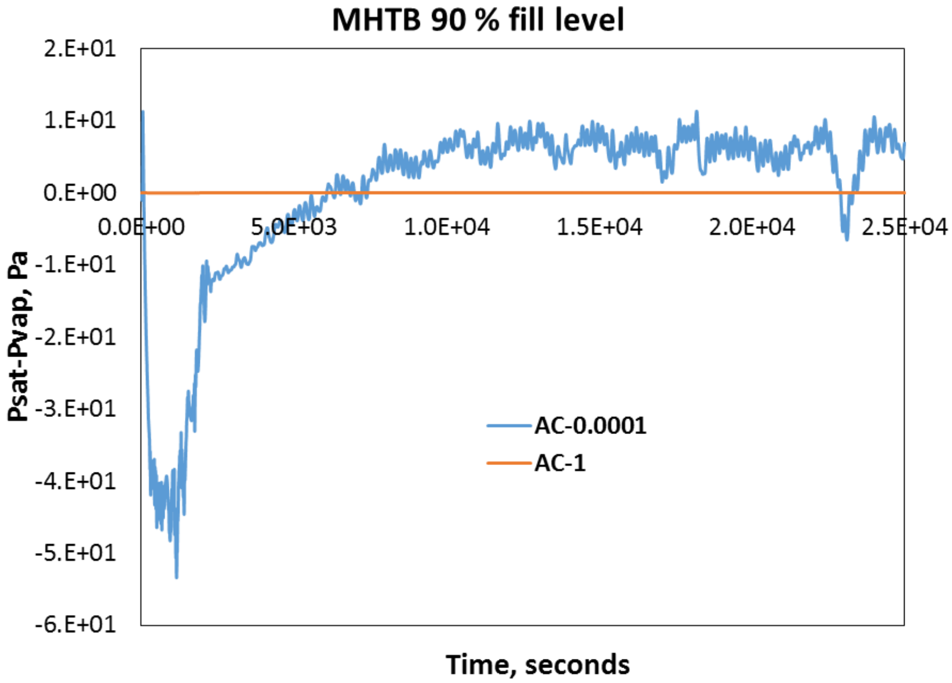


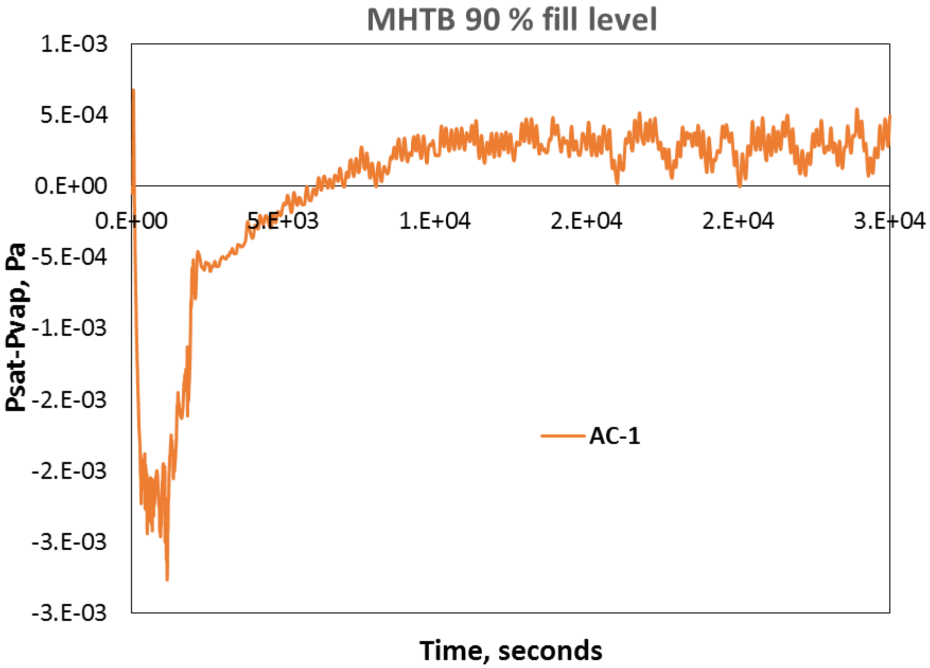
$$|\dot{\mathbf{m}}| = \left(\frac{2\sigma}{2-\sigma}\right)\left(\frac{M}{2\pi R}\right)^{1/2}\left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}}\right) \qquad (7)$$

Effect of Accommodation Coefficient- (MHTB 90%)

Sharp Interface Model

Heat Flux = 2.05 W/m^2

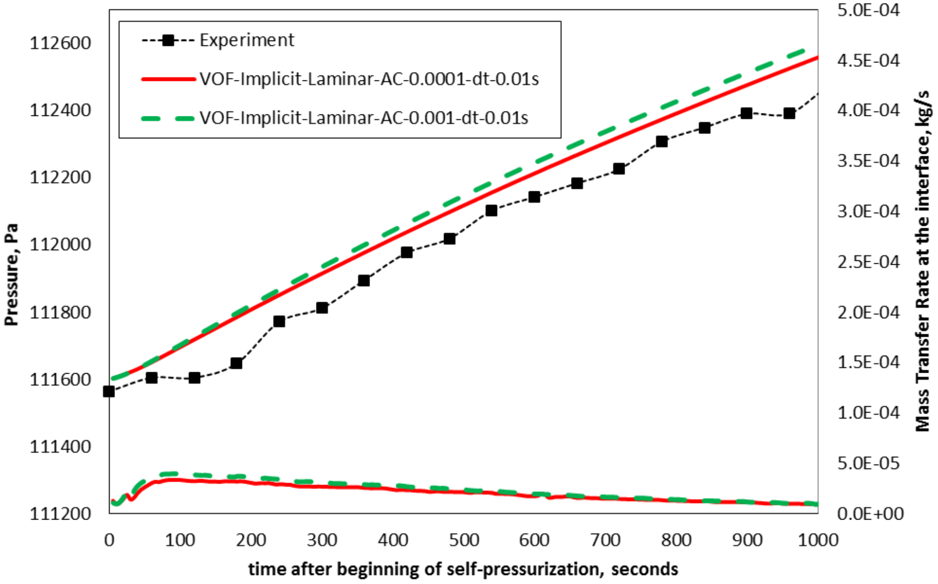




$$|\dot{\mathbf{m}}| = \left(\frac{2\sigma}{2-\sigma}\right)\left(\frac{M}{2\pi R}\right)^{1/2}\left(\frac{P_{sat}(T_i) - P_v}{T_i^{1/2}}\right) \tag{8}$$

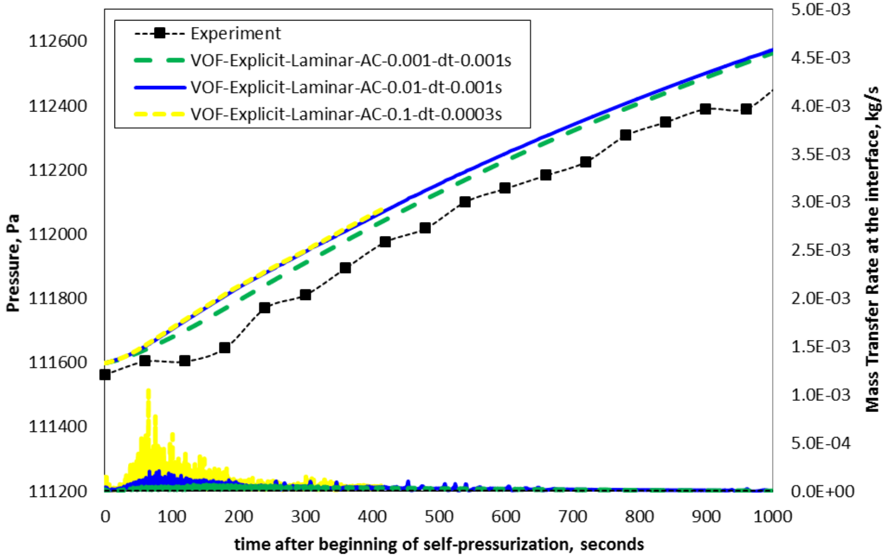
Effect of Accommodation Coefficient - MHTB (50%)

VOF Model

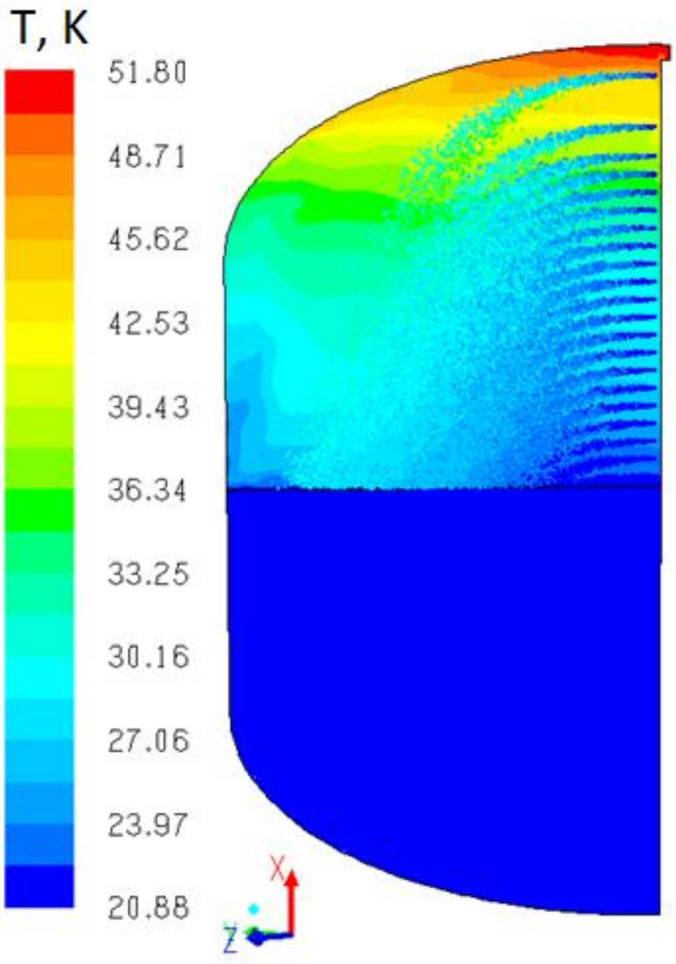


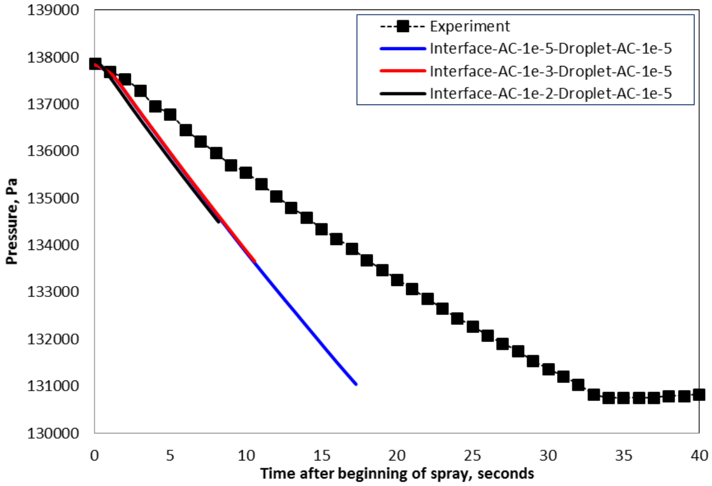
Liquid Heat Flux = 2.05 W/m^2

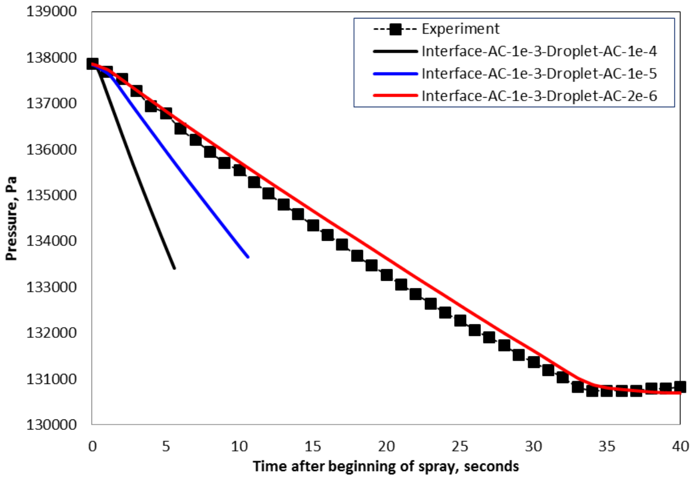
Vapor Heat Flux = 0.90 W/m^2



1G MHTB Pressure Control Results: LH2, Large Tank Droplet Spray Bar - VOF







Effect of Accommodation Coefficient - Summary

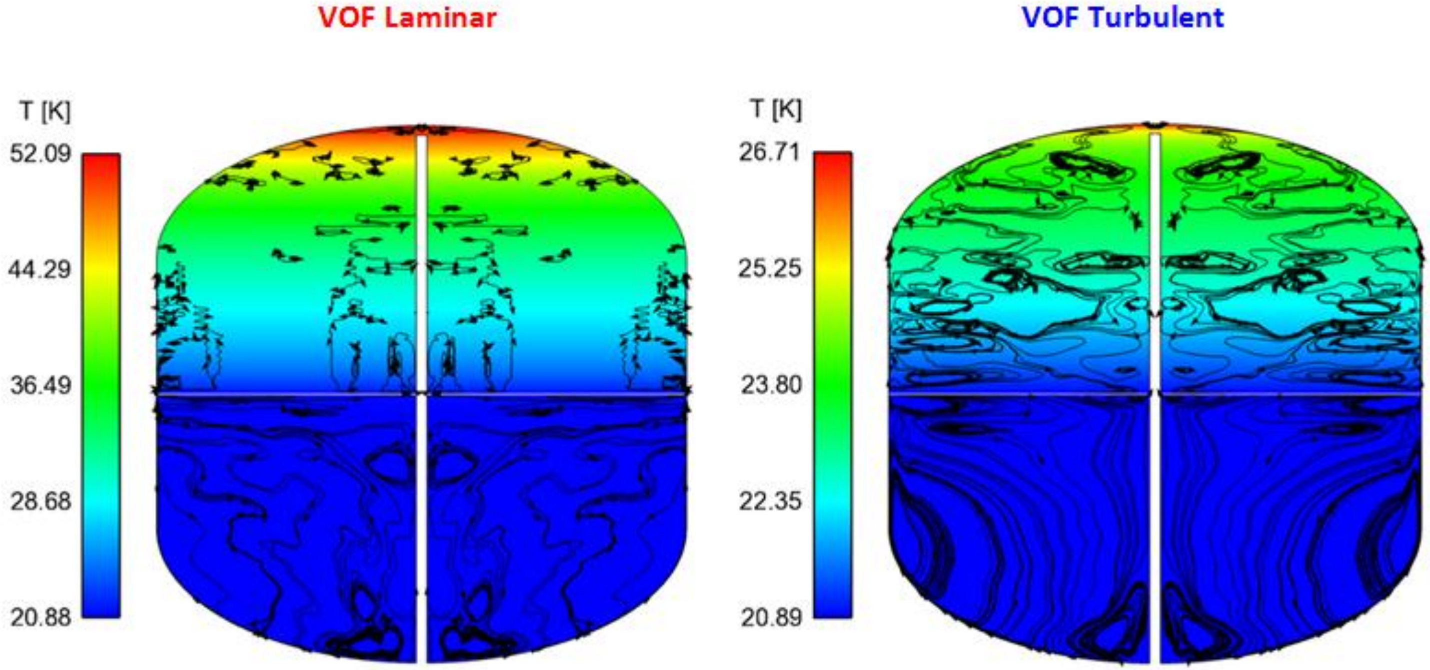
- Computation of mass transfer using Shrage in the sharp Interface model is insensitive to the magnitude of accommodation coefficient. α close to 1 seems to work fine.
- Computations of mass transfer using Schrage in the VOF method also show a certain degree of insensitivity to the magnitude of accommodation coefficient but small values around $\alpha = .01$ seem to be necessary for numerical practicality and stability
- This is only true for a stable flat interface between bulk phases. Mass transfer computations based on Schrage equation for droplets and during slosh dynamics or boiling situations are quite sensitive to magnitude of accommodation coefficient.
- Schrage might not represent the right mass transfer kinetics under these conditions.

Effect of Turbulence

Effect of Turbulence: MHTB (50%)

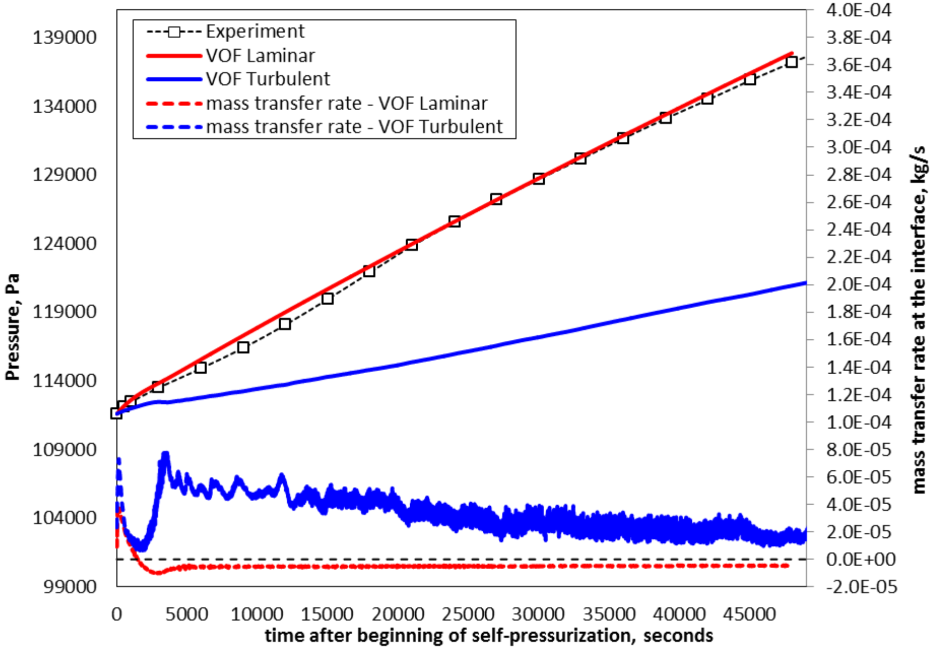
Liquid Heat Flux = 2.05 W/m^2

Vapor Heat Flux = 0.90 W/m^2



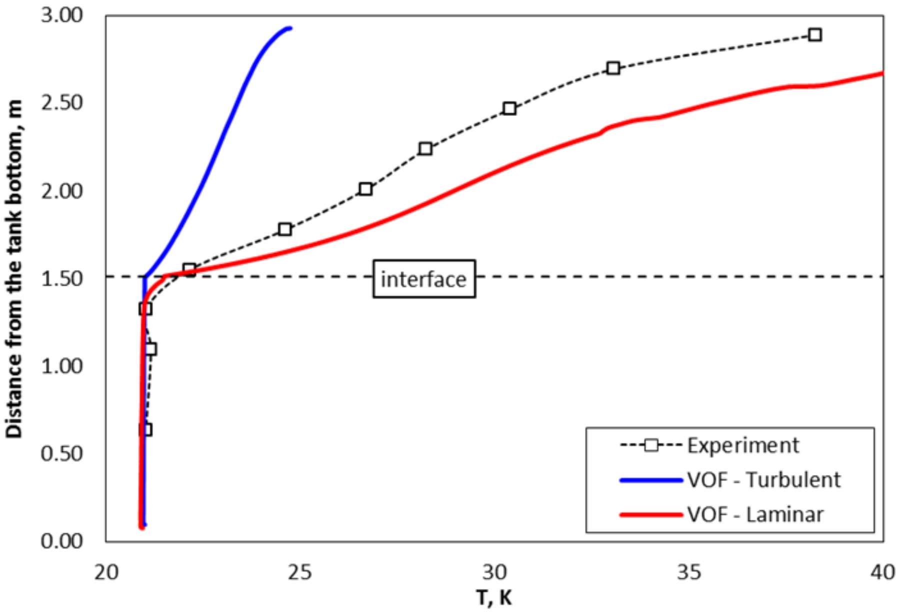
MHTB Self Pressurization: Effect of Turbulence

Pressure Time History



Laminar vs. Turbulent

Temp Profile at end of Self-Press

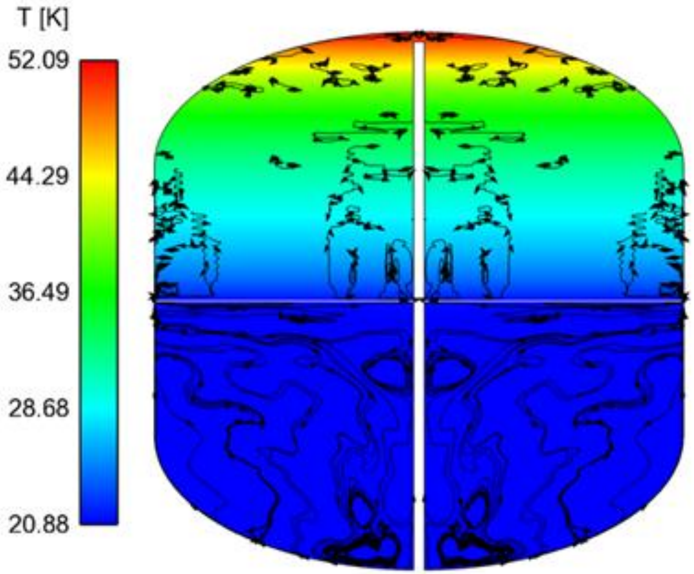


Liquid Heat Flux = 2.05 W/m^2

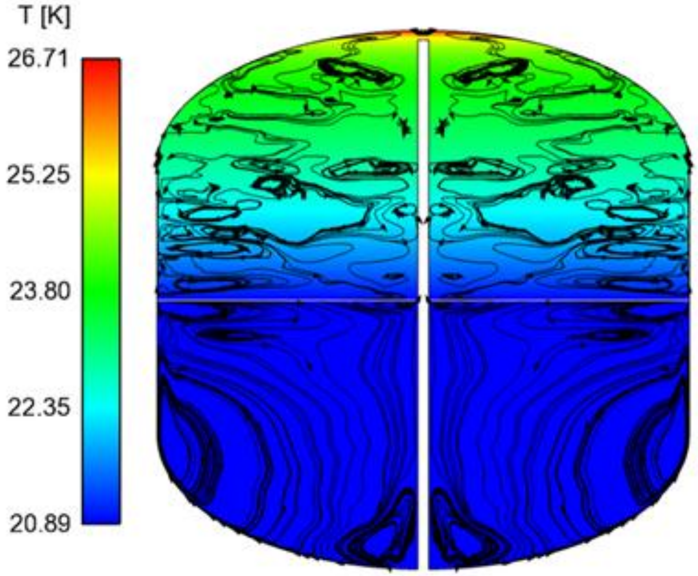
Vapor Heat Flux = 0.90 W/m^2

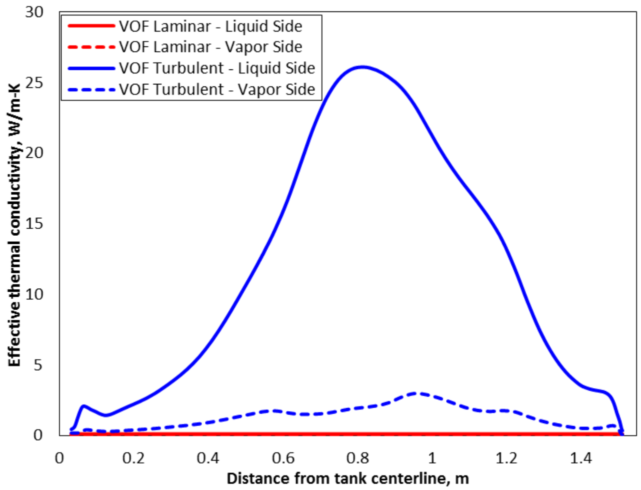
MHTB Self-Pressurization: Effect of Turbulence

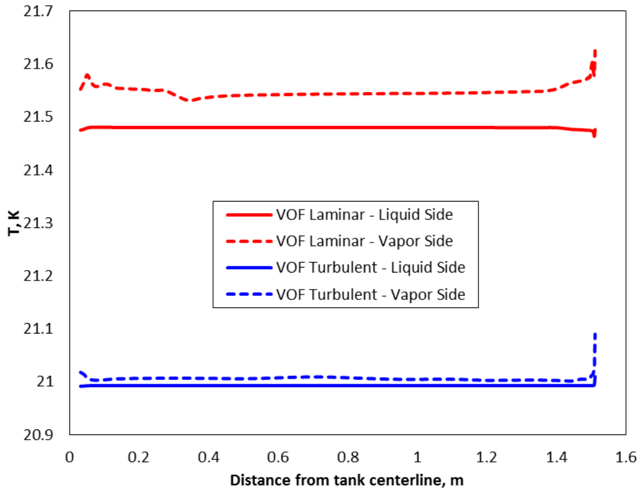
VOF Laminar



VOF Turbulent

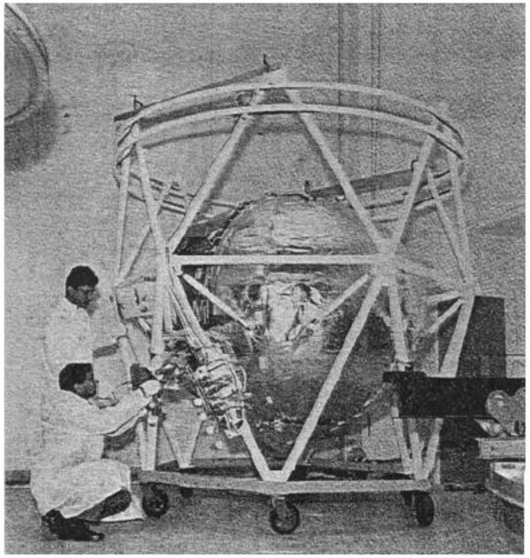


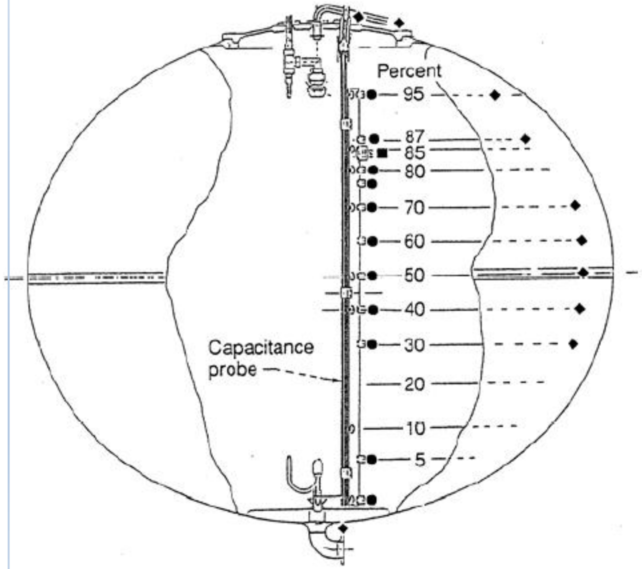




Tank Self-Pressurization Experiments at K-site Facility (1990-91)

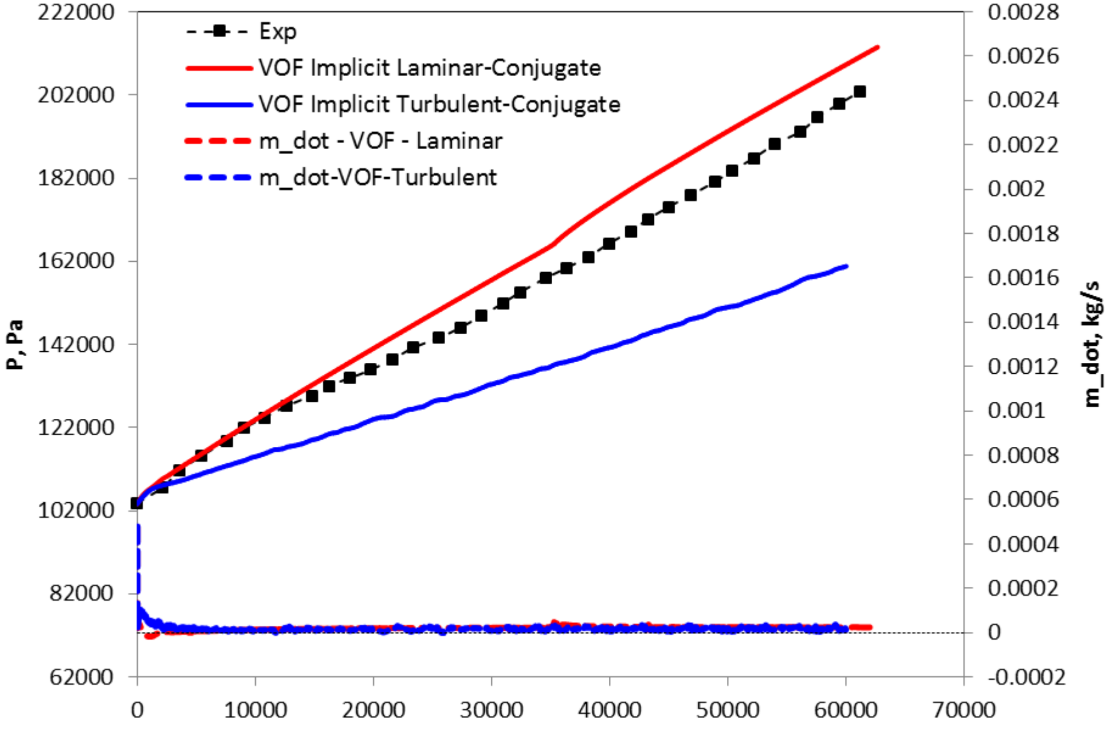
1. Test fluid is liquid **hydrogen**
2. Flightweight insulated 2219-T62 aluminum ellipsoidal tank
   - Internal volume: **4.95 m^3** = 175 ft^3
   - Tests conducted in vacuum chamber.
   - Test article is enclosed by a cryoshroud whose temperatures are maintained with electrical heaters.
   - Tank is insulated with 2 blankets of MLI.
3. Steady boil-off test and measurement performed at 95% liquid fill fraction and 117 kPa (or 1.17 bar) tank pressure.
4. Tank fill level was reduced to desired fill level (29%, **49%,** 83%)
5. Several hours of additional venting at 103 kPa were performed to achieve stationary state.
6. Self-pressurization tests were initiated from a stationary stratified state.
7. Two Cryoshroud Temps → Two heat loads (**2 & 3.5 W/m^2**)
8. Grashof Number (Gr) based on 3.5 W/m^2 average heat flux into tank → **vapor: Gr = 2.21e+13; liquid: Gr = 1.33e+14** (which corresponds to turbulent natural convection for a steady-state natural convection flow)



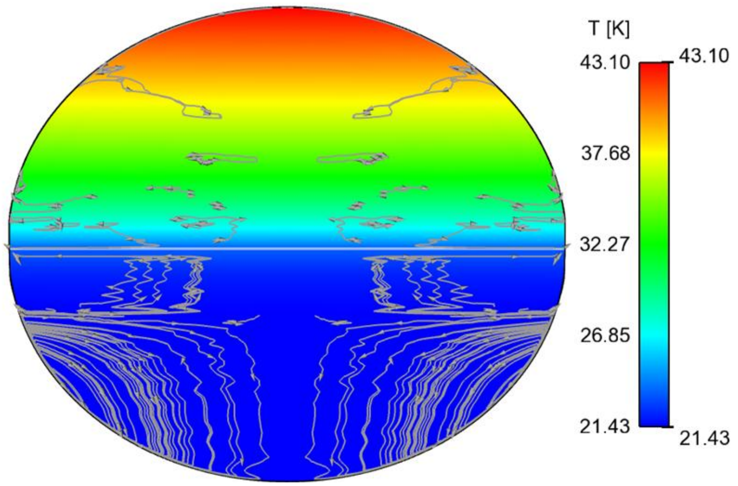


Effect of Turbulence: K-Site (50%)

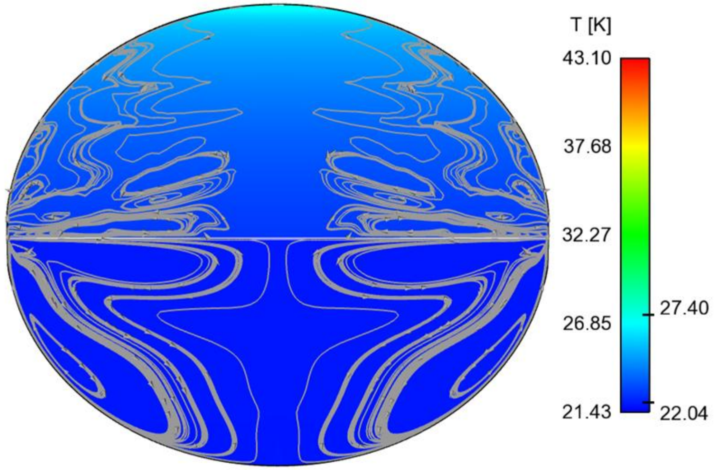
Tank Pressure & Interfacial Mass Transfer



K-Site VOF, Conjugate HT, Laminar, 3.5 W/m^2



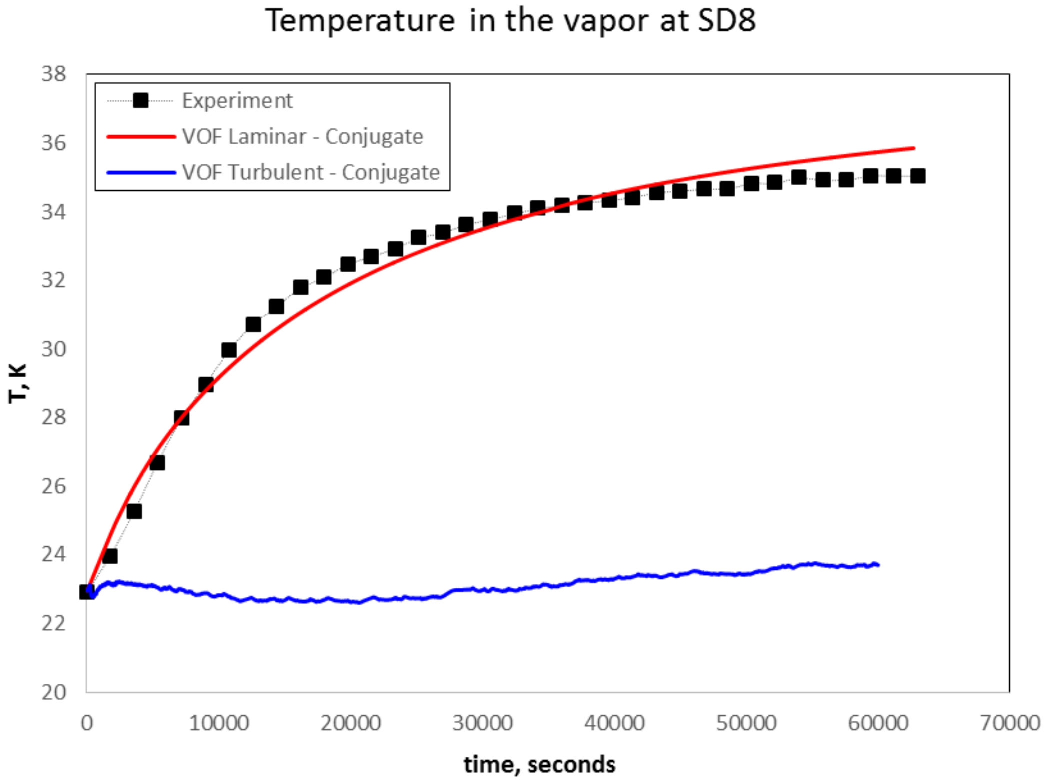
K-Site VOF, Conjugate HT, Turbulent, 3.5 W/m^2

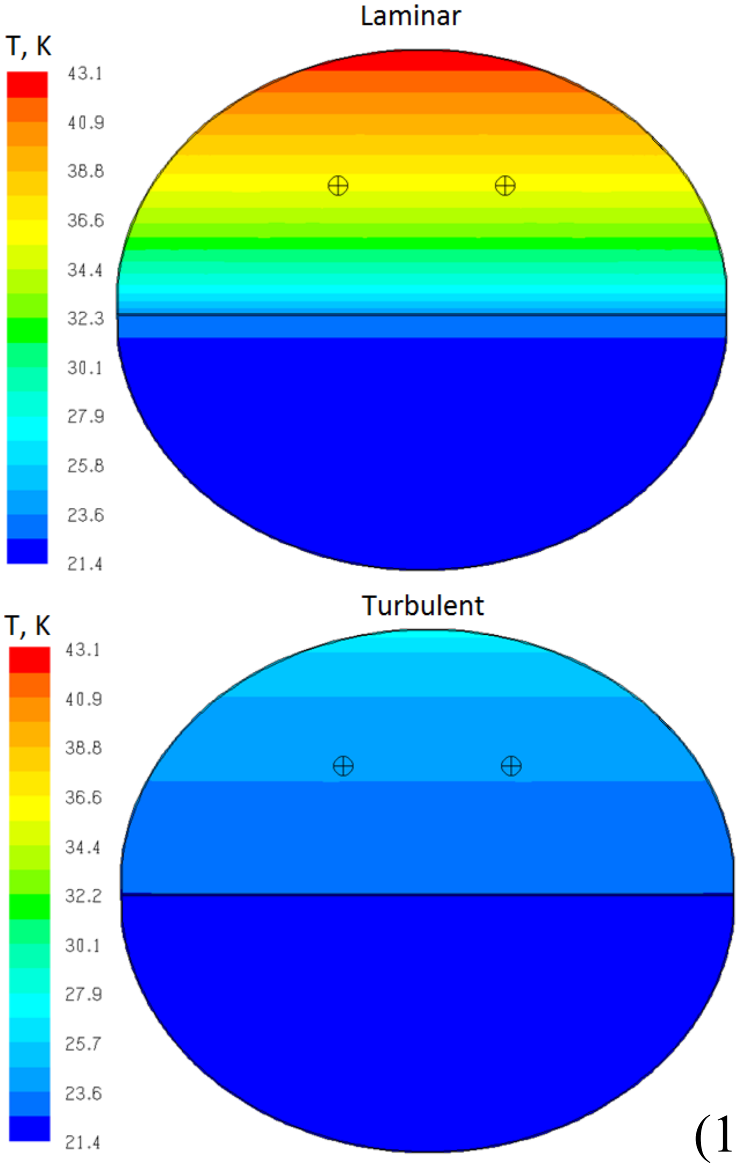


60,000 seconds of self-pressurization

K-Site Self-Pressurization: Effect of Turbulence

Results: 3.5 W/m^2 heat flux

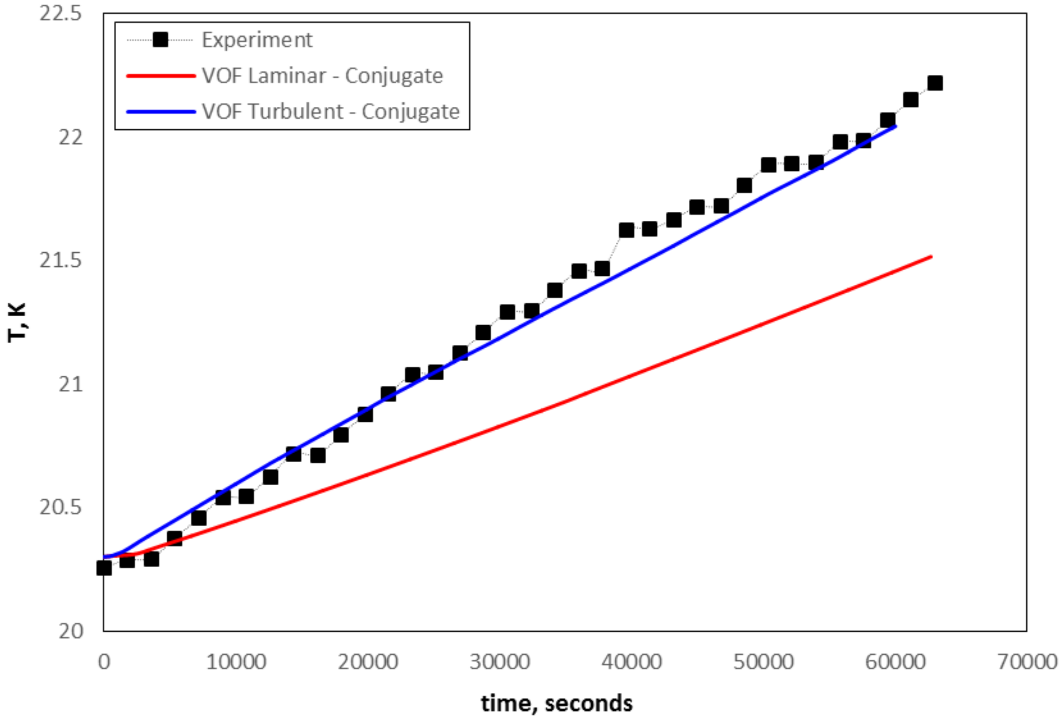




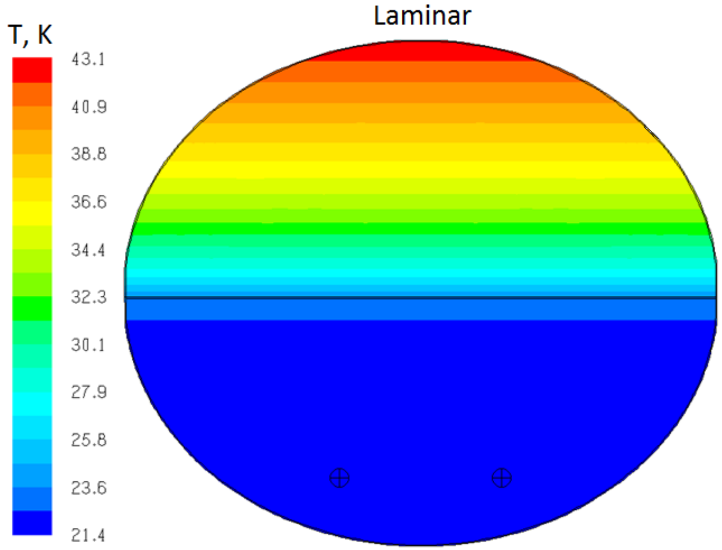
K-Site Self-Pressurization: Effect of Turbulence

Results: 3.5 W/m^2 heat flux

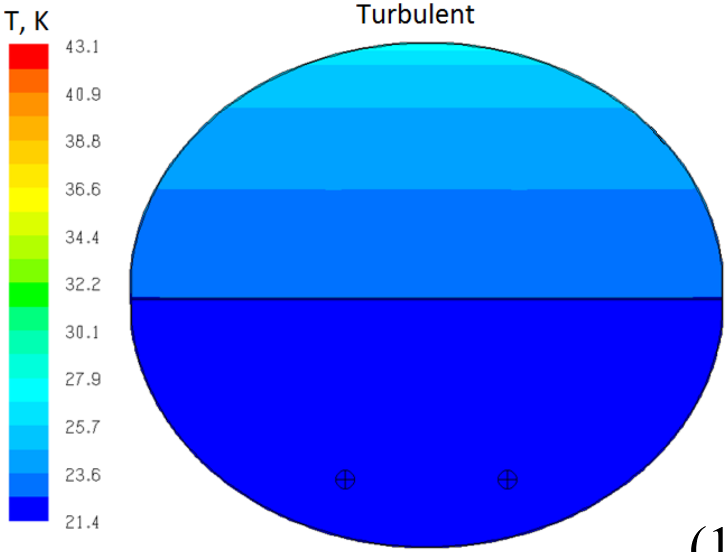
Temperature in the liquid at SD16



Laminar

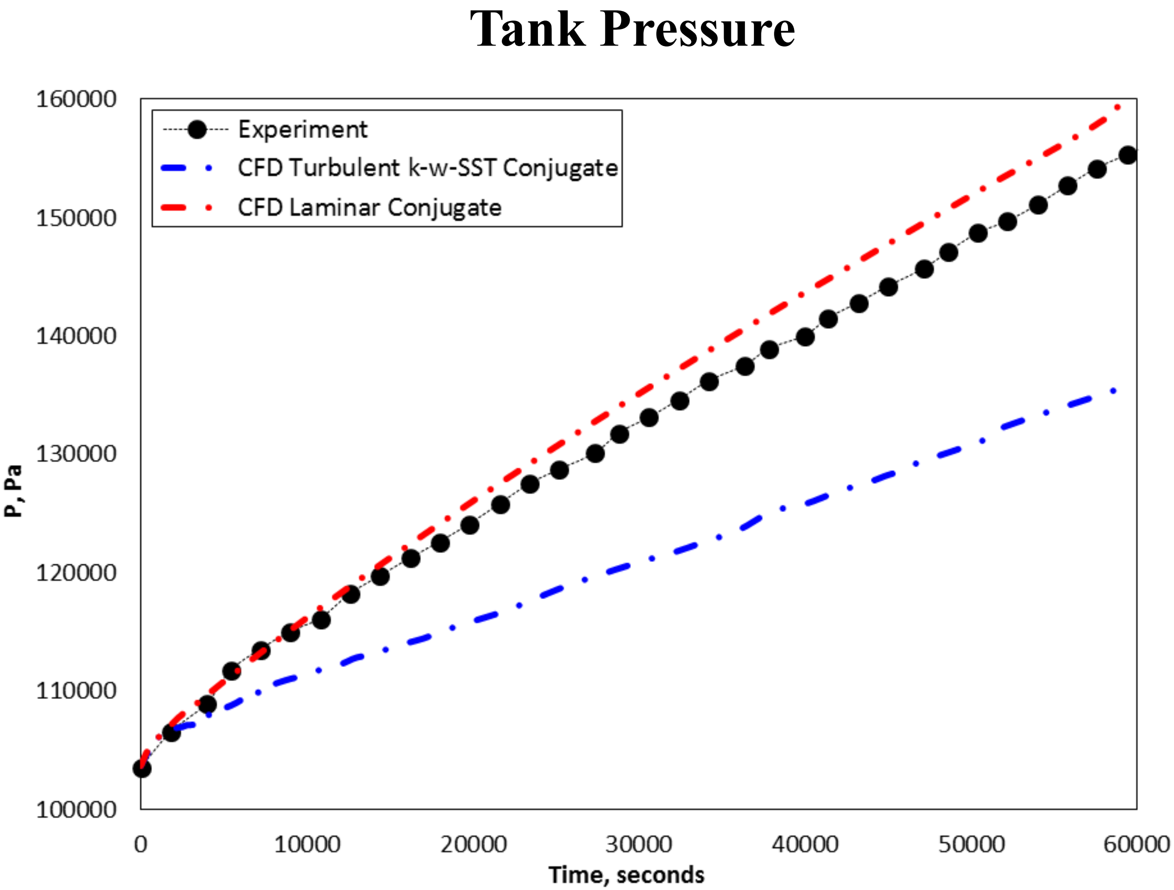


Turbulent

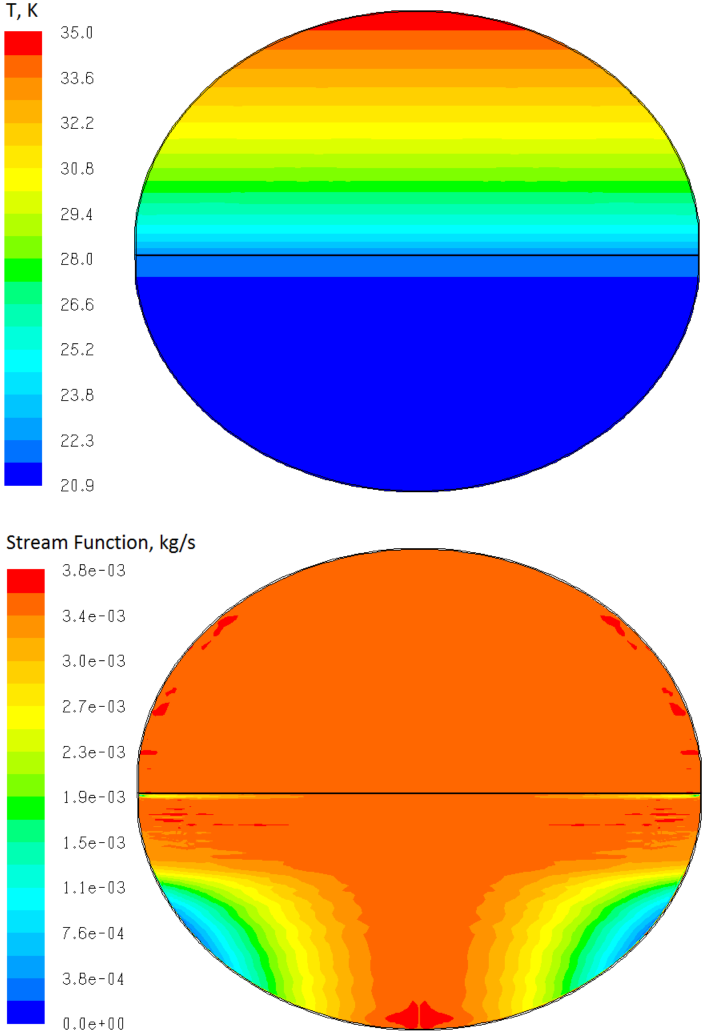


K-Site Self-Pressurization: Effect of Turbulence

Results: 2.0 W/m^2 heat flux



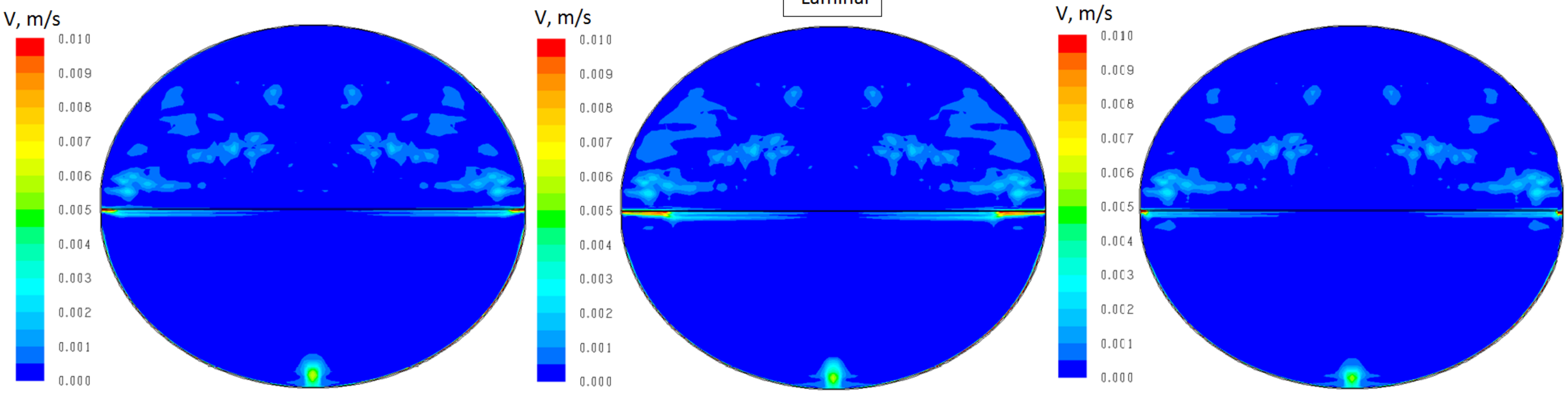
CFD Laminar Conjugate
End of Self-Pressurization



K-Site Self-Pressurization: Effect of Turbulence

Velocity Magnitude

Laminar

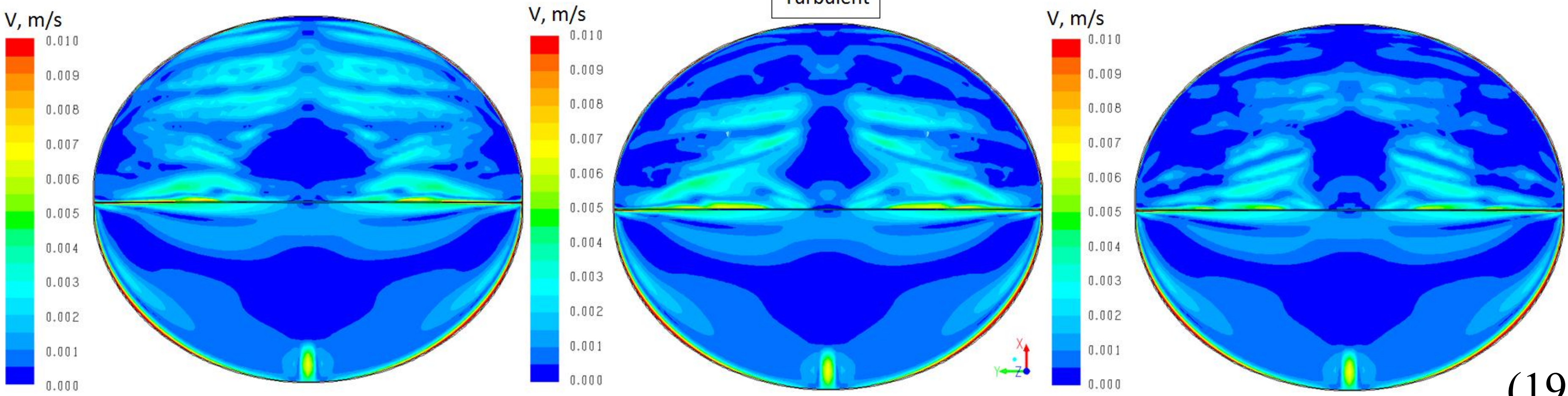


10000 seconds

30000 seconds

60000 seconds

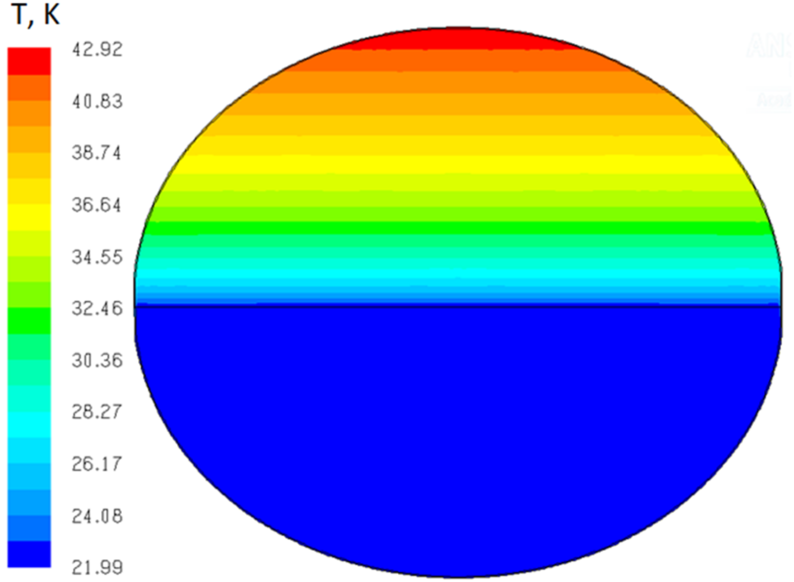
Turbulent

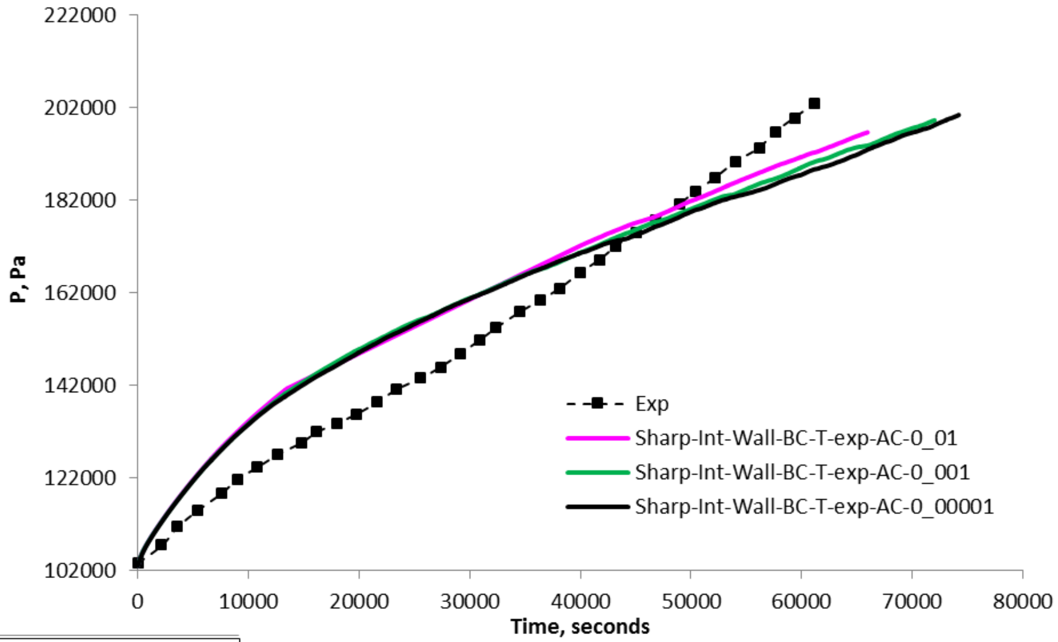


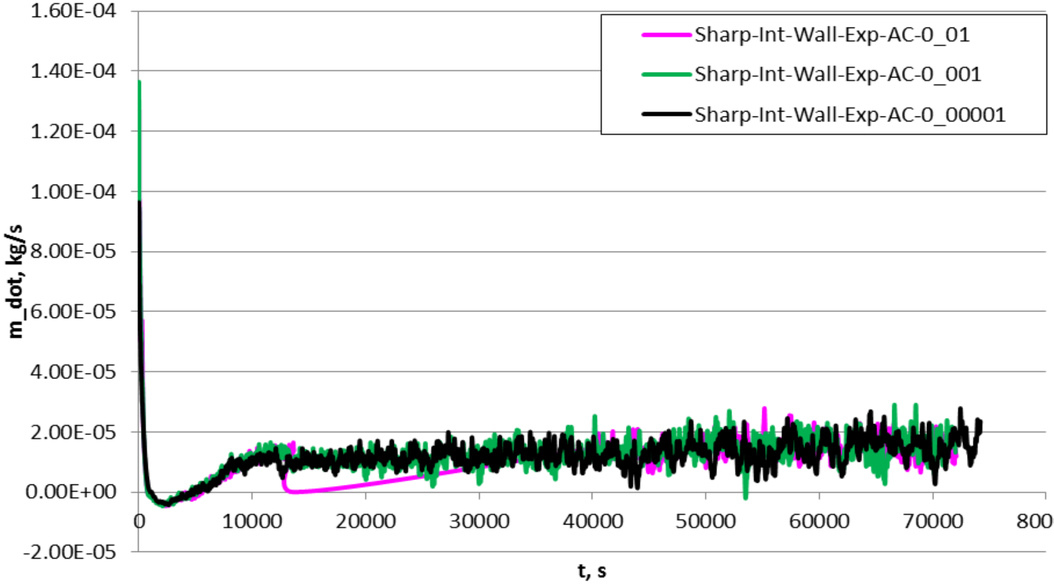
Effect of Turbulence- Summary

- Laminar models agree closely with the pressure evolution and vapor phase temperature stratification but under-predict liquid temperatures.
- Turbulent SST k-w and k-e models under-predict the pressurization rate and extent of stratification in the vapor but represent liquid temperature distributions fairly well.
- These conclusions seem to equally apply to large cryogenic tank simulations as well as small scale simulant fluid pressurization cases.
- Appropriate turbulent models that represent both interfacial and bulk vapor phase turbulence with greater fidelity are needed.
- Application of LES models to the tank pressurization problem can serve as a starting point.

K-Site Self-Pressurization: Effect of Turbulence Sharp Interface Model







Results: 3.5 W/m^2 heat flux

(A1)