To be Presented at the 30th Space Cryogenics Workshop, Kailua-Kona, Hawaii, July 16-18, 2023

CFD Modeling of a Cryogenic Methane Drain Test with and without Induced Sloshing

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CSA 30th Space Cryogenics Workshop, July 16-18, 2023

Outline

- Overview of the experiment and CFD Model Setup
- CFD Results
  - Static Pressurization and Drain Test (Case 8)
    - Laminar Results
    - Effect of Accommodation Coefficient
    - Effect of modeling turbulence and phase change at the interface.
    - Effect of turbulence damping at the interface
  - Sloshing-Pressurization and Drain Test (Case 29)
    - Laminar Results
- Conclusions and Forward Work

NASA K-Site LCH4 Experimental Results (Effect of Slosh on Methane-Pressed Cases)

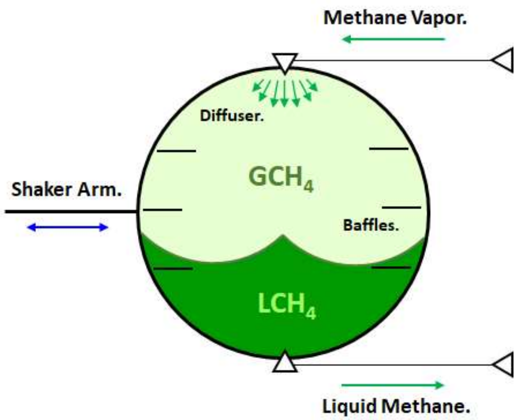
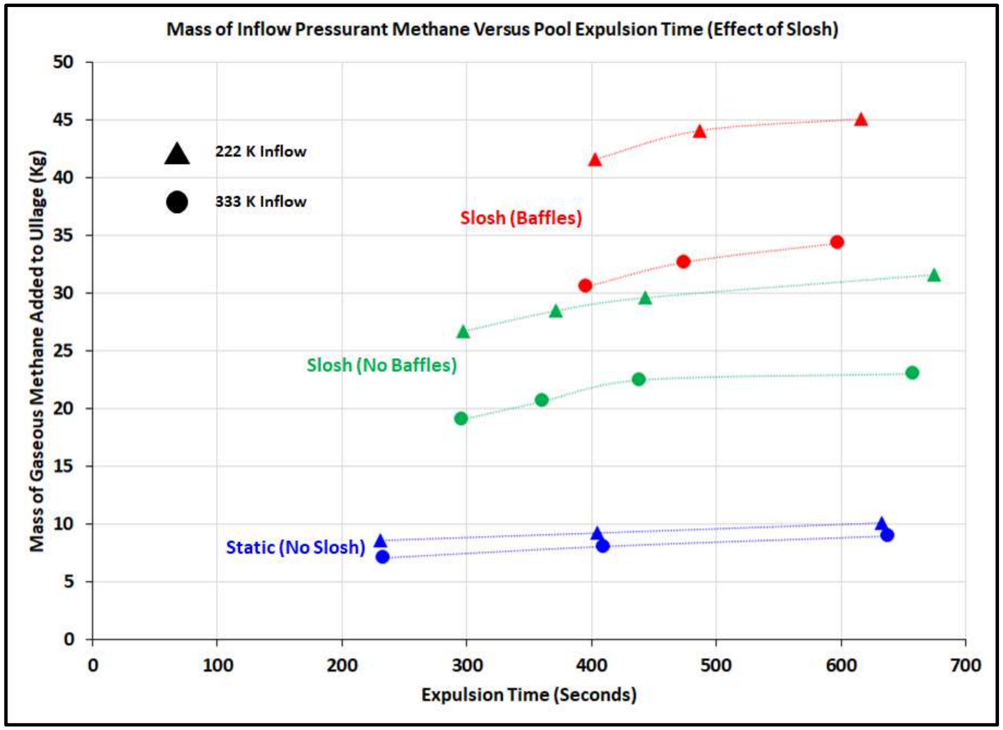


Chart Shows Experimental Data Only



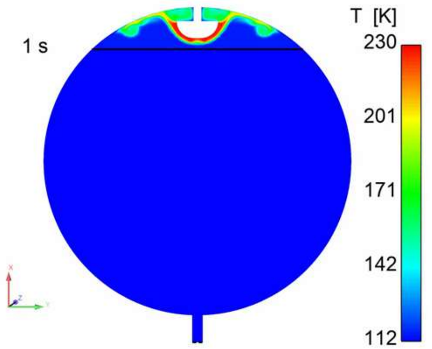
Sloshing significantly increased the autogenous pressurant mass required to expel propellant from the propellant tank

Expulsion Test Description

- Pressurization and expulsion tests were conducted at Armstrong Test Facility with liquid methane using a 5 ft diameter spherical aluminum tank in 1974.
  - The draining portions of the experiments were conducted with and without induced sloshing.
  - Drain test was conducted using multiple pressurants: methane, helium, hydrogen, nitrogen.
- The test and test results were used to validate and anchor FLUENT VOF CFD models by comparing the predicted pressurant mass and temperatures against experimental measurements that were documented in the 1974 test report.
- Several CFD simulations were run to investigate the following effects:
  - Grid/Mesh Independence
  - Accommodation Coefficient
  - Laminar vs K-omega SST Turbulence Models
  - Turbulence Damping

5 ft Diameter Spherical Tank and Test PI(Robert Stochl)

ANSYS FLUENT CFD Predicted Temperatures During Static Drain (Case 8)



DeWitt, R. L., & McIntire, T. O., "Pressurant Requirements for Discharge of Liquid Methane from a 1.52- Meter- (5-ft-) Diameter Spherical Tank Under Both Static and Slosh Conditions," NASA-TN-D-7638, 1974.

Computational Model: VOF Governing Equations

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:

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

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 Liquid/Vapor Mass Transfer (Schrage's Relation) :

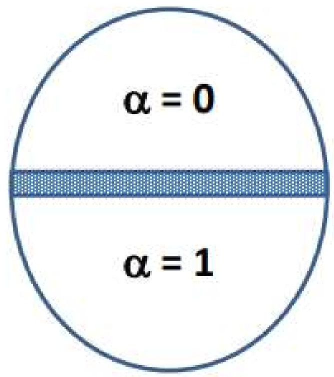
$$|\dot{\mathbf{m}}| = \left(\frac{2\sigma}{2-\sigma}\right)\left(\frac{M}{2\pi R}\right)^{1/2}\left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}}\right), \left[\frac{kg}{m^2 \cdot \sec}\right]$$

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).



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:

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

Continuum Surface Force (Brackbill et al.):

$$F_{vol} = \sum_{\text{pairs } ij,\, i<j} \sigma_{ij} \frac{\alpha_i \rho_i h_j \nabla \alpha_j + \alpha_j \rho_j h_i \nabla \alpha_i}{\frac{1}{2}\left(\rho_i + \rho_j\right)}$$

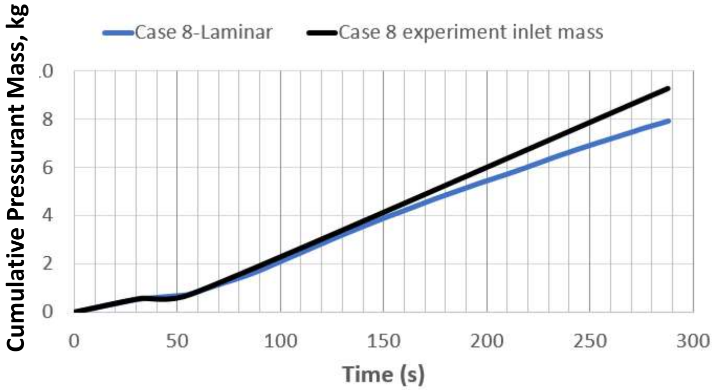
Static Drain Case 8

Methane Pressurant Inlet Temperature:222 K

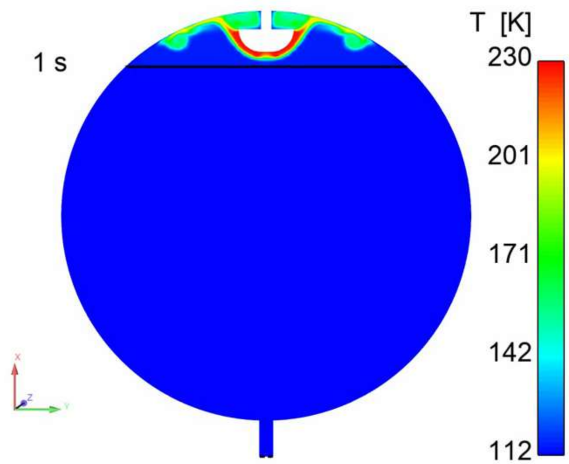
Liquid Expulsion Time: 232 seconds

Liquid Methane Drain Test Modeling (Case 8) -Laminar-Accommodation Coefficient:0.01 (2D-axi)

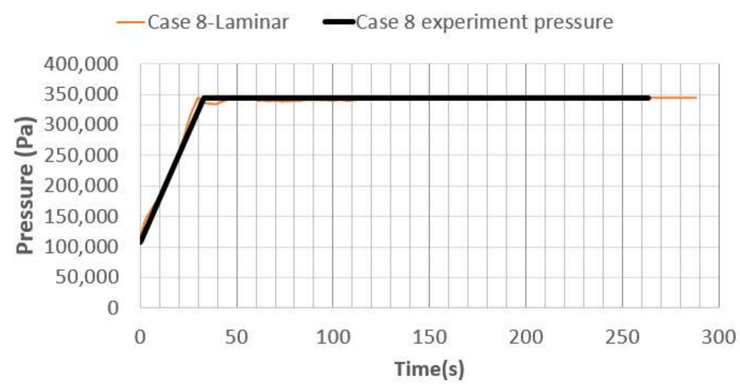
Predicted Pressurant Mass vs Exp Mass



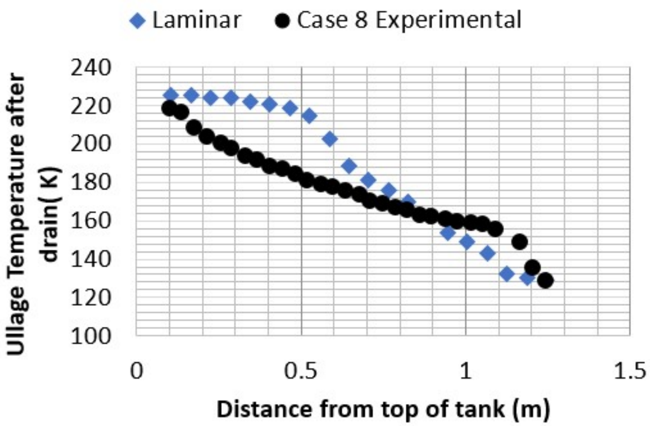
FLUENT(Laminar) Predicted Temperatures



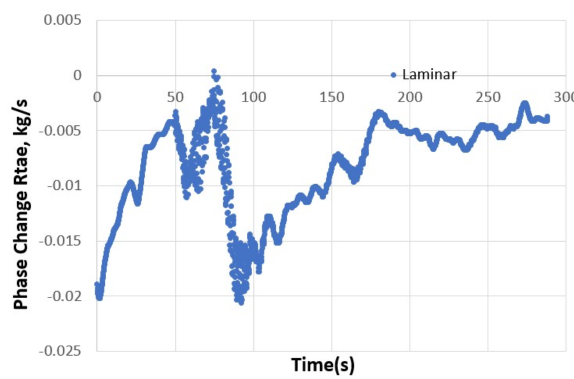
Predicted vs Exp Pressure



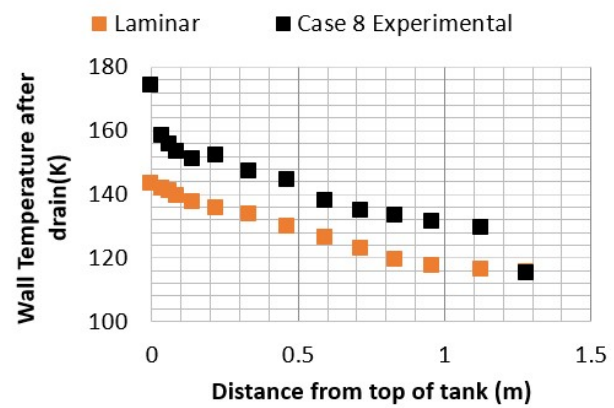
Predicted Ullage Temperature after Drain vs Exp



Phase Change Rate (Predicted)

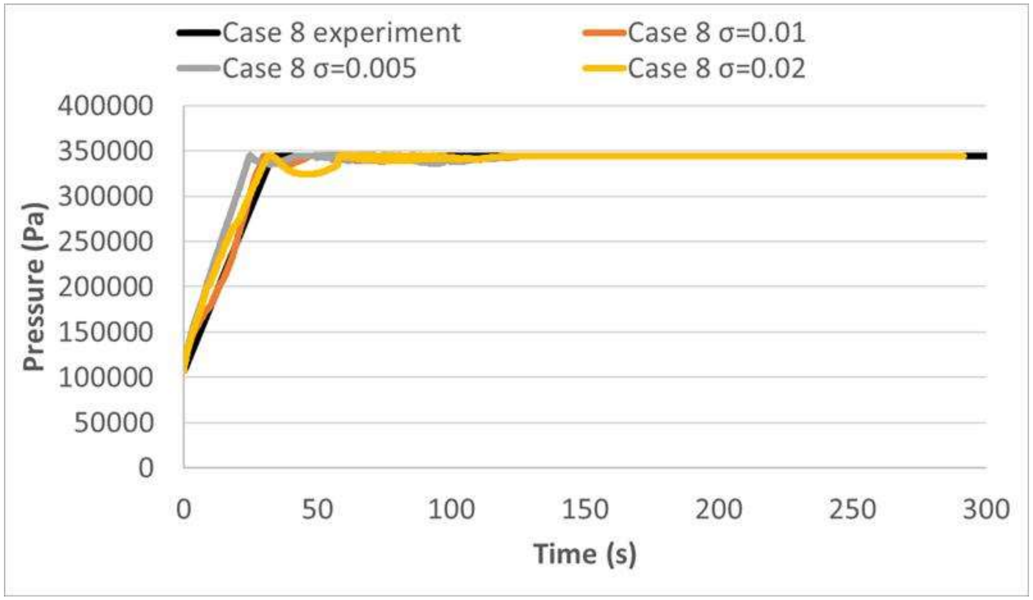


Predicted Wall Temperature after drain vs Exp

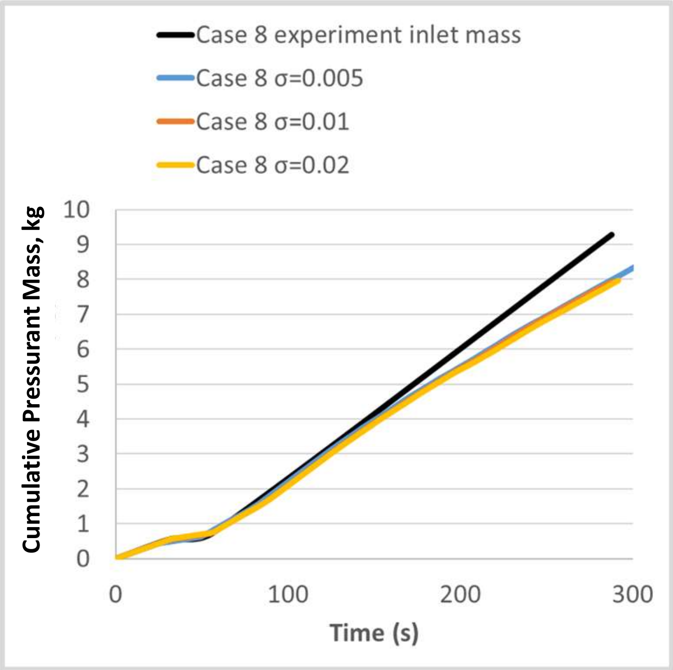


Liquid Methane Static Drain Test (Case 8)
-Laminar- Accommodation Coefficient Varied: 0.005-0.02

Predicted Pressurant (CFD,FLUENT) Mass For Case 8 vs Exp Mass



Simulated vs Exp Pressure (Case 8)



Pressurant mass predictions were found to be independent of accommodation coefficient.

Static Drain Case 8

Methane Pressurant Inlet Temperature:222 K

Liquid Expulsion Time: 232 seconds

Include effects of Turbulence

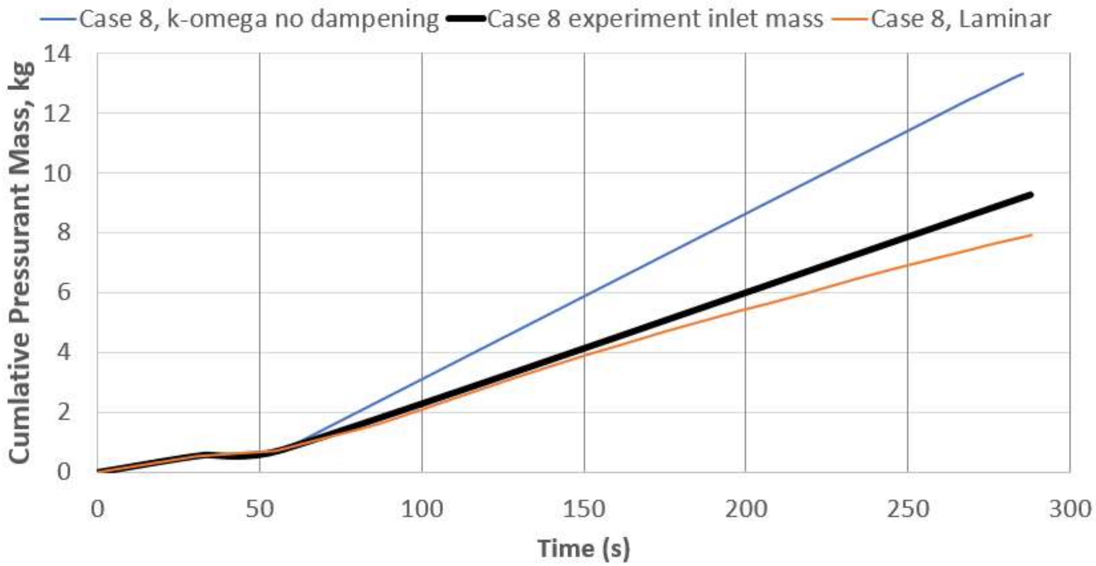
k-omega Shear Stress Transfer Two Equation Turbulence Model

$$\frac{D}{Dt}(\rho\omega) = \nabla \cdot (\rho D_\omega \nabla\omega) + \frac{\rho\gamma G}{\nu} - \frac{2}{3}\rho\gamma\omega(\nabla \cdot \mathbf{u}) - \rho\beta\omega^2 - \rho(F_1 - 1)CD_{k\omega} + S_\omega,$$

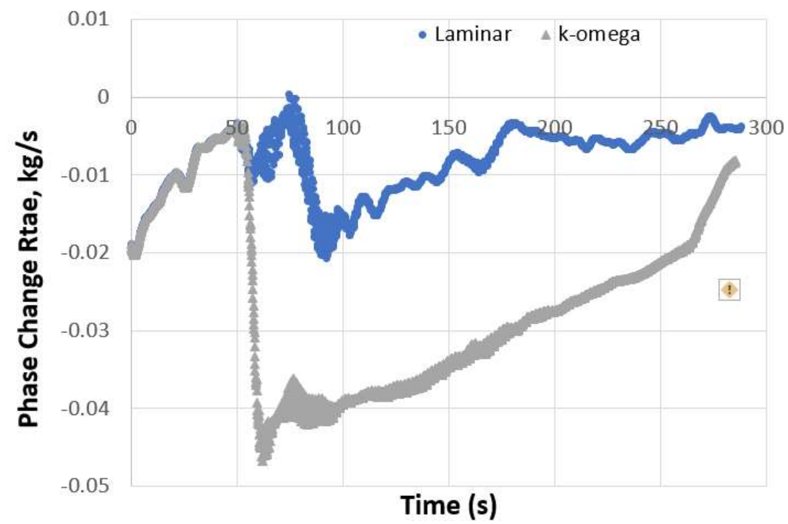
$$\frac{D}{Dt}(\rho k) = \nabla \cdot (\rho D_k \nabla k) + \rho G - \frac{2}{3}\rho k(\nabla \cdot \mathbf{u}) - \rho\beta^* \omega k + S_k.$$

Liquid Methane Static Drain Test (Case 8)
-K-omega-SST Turbulence Model, Accommodation Coefficient:0.01

Predicted Pressurant vs Exp Mass



Phase Change Rate (predicted Laminar vs Turbulent)



Turbulence increases the phase change rate, and over predicts the required pressurant mass

Static Drain Case 8

Methane Pressurant Inlet Temperature:222 K

Liquid Expulsion Time: 232 seconds

Include turbulence damping at the liquid/vapor interface

k-omega Shear Stress Transfer Two Equation Turbulence Model

$$\frac{D}{Dt}(\rho\omega) = \nabla\cdot(\rho D_\omega \nabla\omega) + \frac{\rho\gamma G}{\nu} - \frac{2}{3}\rho\gamma\omega(\nabla\cdot\mathbf{u}) - \rho\beta\omega^2 - \rho(F_1 - 1)CD_{k\omega} + S_\omega,$$

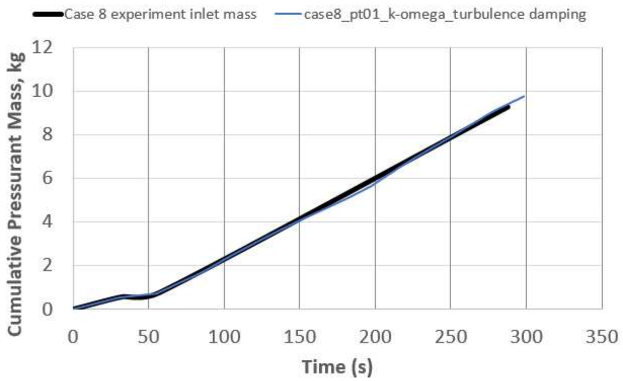
$$\frac{D}{Dt}(\rho k) = \nabla\cdot(\rho D_k \nabla k) + \rho G - \frac{2}{3}\rho k(\nabla\cdot\mathbf{u}) - \rho\beta^* \omega k + S_k.$$

Turbulence Damping Coefficient

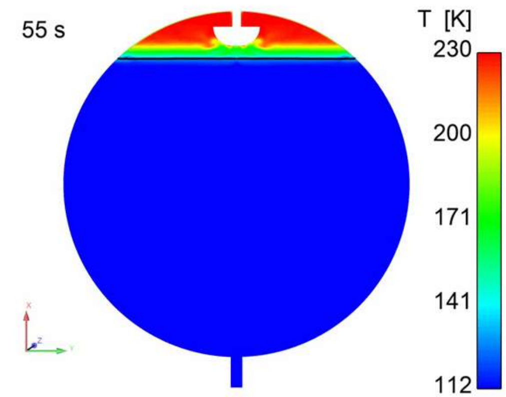
$$S_i = A_i \Delta n \beta \rho_i \left(\frac{B\,6\,\mu_i}{\beta \rho_i \Delta n^2} \right)^2,$$

Liquid Methane Drain Test Modeling (Case 8)
-k-omega w/dampening-Accommodation Coefficient:0.01

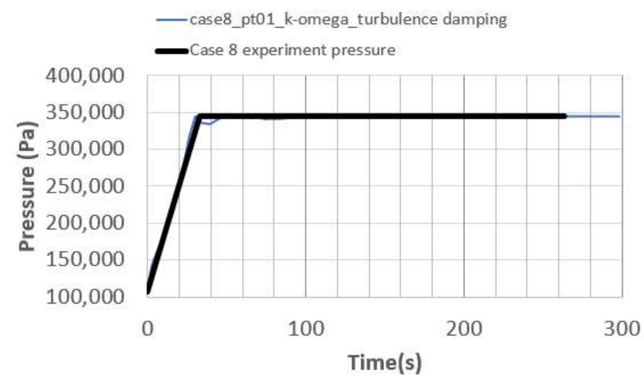
Predicted Pressurant Mass vs Exp Pressurant Mass



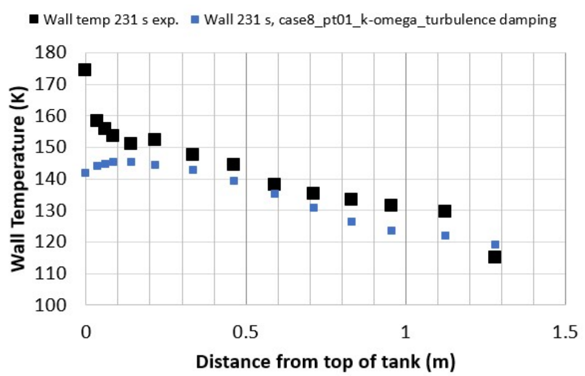
Fluent Predicted Temperatures During Static Drain



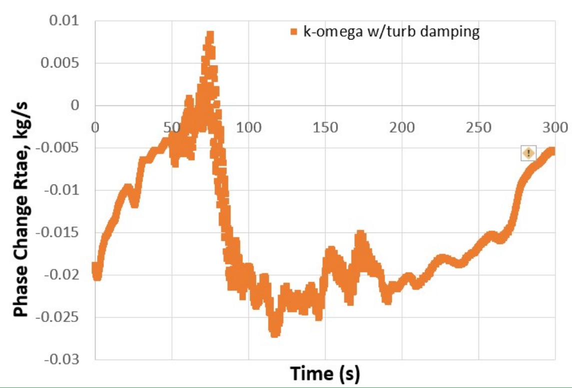
Predicted vs Exp Pressure



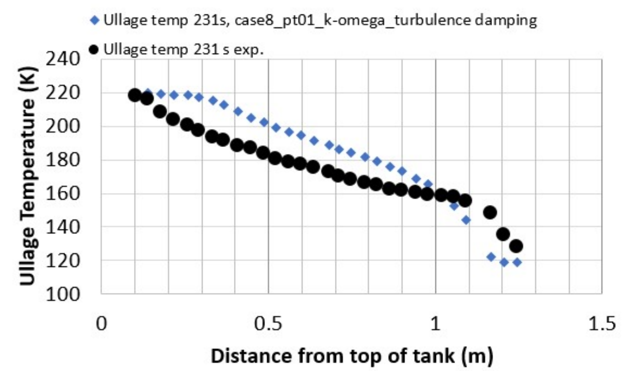
Predicted vs Exp Final Wall Temperature



Phase Change Rate (Predicted)



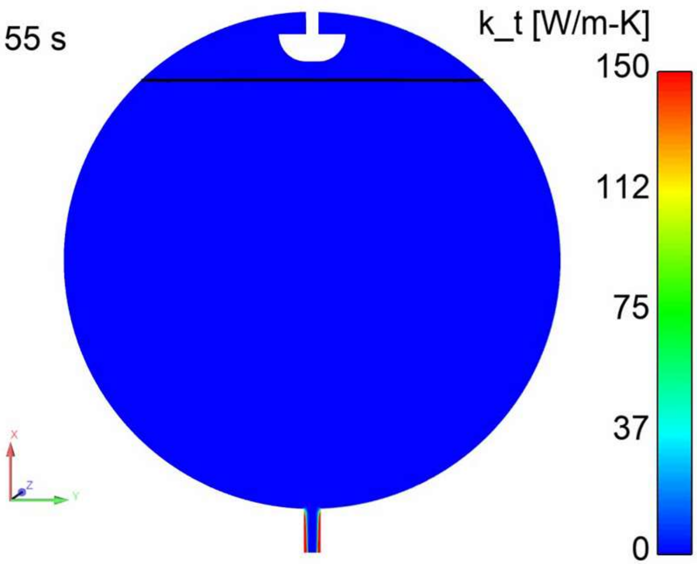
Predicted vs Exp Final Ullage Temperature



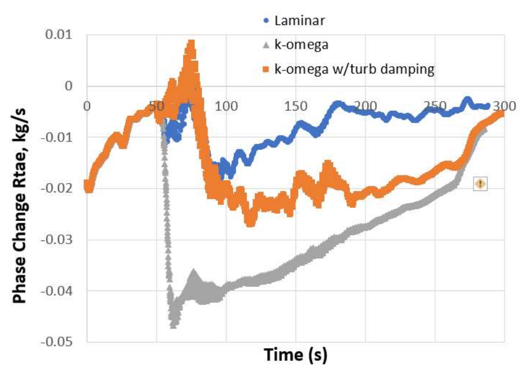
Turbulence with damping at the liquid/vapor interface results in a more accurate prediction of required pressurant mass and final ullage wall temperatures.

Effective Liquid Thermal Conductivity with and without Turbulence Damping
(Liquid Molecular Thermal Conductivity(Laminar)=0.18 Watt/m-K @112 K)

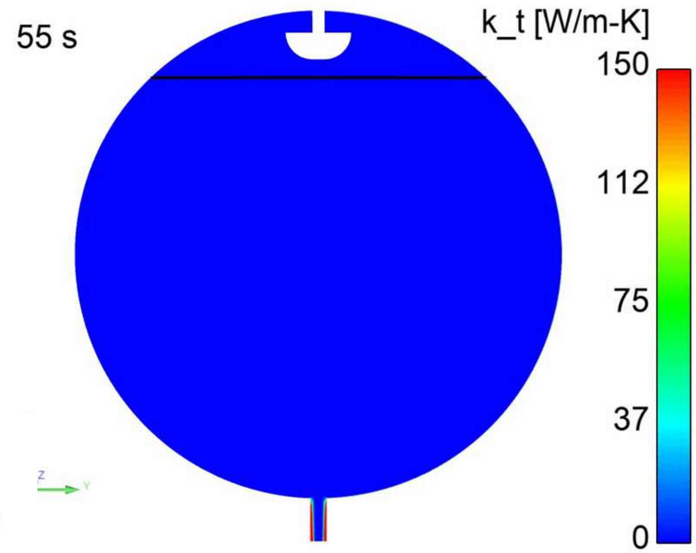
Thermal Conductivity (Turbulence without Damping)



Phase Change Rate



Thermal Conductivity (Turbulence with Damping)



No turbulence damping at the interface results in significantly greater liquid effective thermal conductivity and as a result larger condensation rates of the injected pressurant gas

Drain with Sloshing (Case 29)

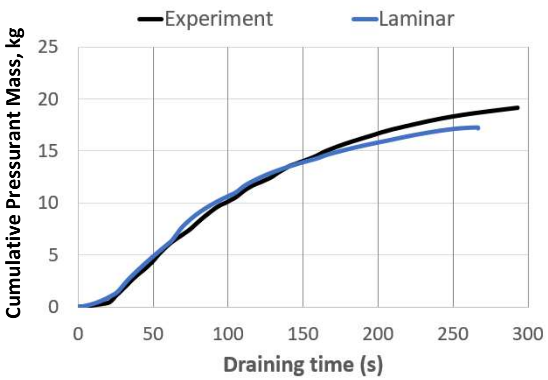
Methane Pressurant Inlet Temperature:333 K

Liquid Expulsion Time: 298 seconds

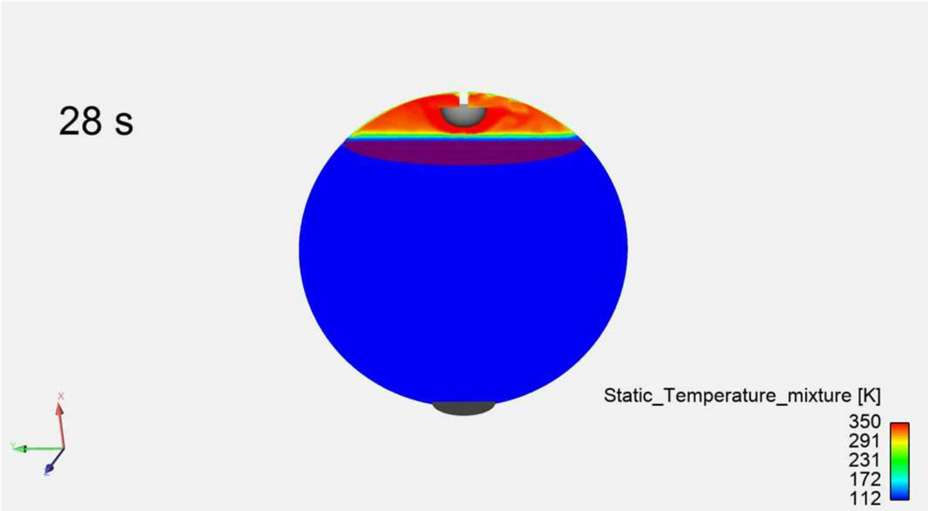
2.23 cm Amplitude at Tank Natural Frequency

Liquid Methane Drain Test Modeling (Slosh Case 29, 2.23 cm Amplitude at Tank NF) Laminar-Accommodation Coefficient:0.01 (3D-VOF)

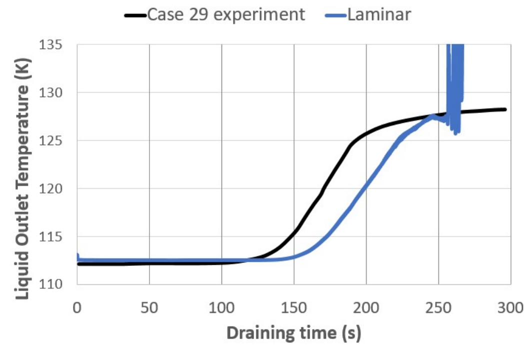
Pressurant Mass Predicted vs Exp Mass (Case 29)



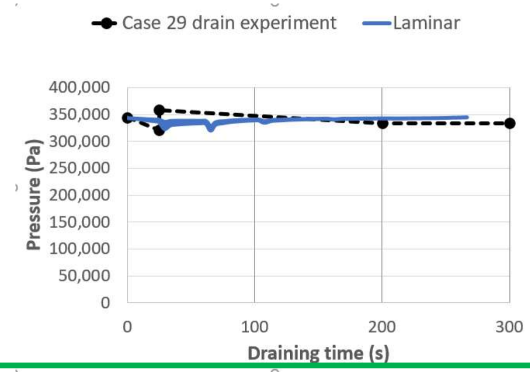
Predicted Temperatures During -Drain with Sloshing (Case 29)



Liquid Outlet Temperature, Predicted vs Exp (Case 29)



Tank Pressure Predicted vs Exp (Case 29)



The preliminary ANSYS FLUENT CFD laminar model predicts the pressurant and liquid outlet temperature to be in a good agreement with the experimental measurements. More work is required to overcome the numerical challenges associated with sloshing with phase change.

Conclusions

- The Ksite liquid methane expulsion tests ran in the 1970's are a unique dataset that can be used to validate pressurization models with and without induced sloshing.
- A multi-phase CFD VOF model previously developed and validated was implemented to model one of the Ksite liquid methane expulsion tests using an autogenous pressurant.
- For the laminar static drain case, the first principal physics ANSYS FLUENT CFD model predicted the required pressurant for the static drain within 12% of the experimentally measured value.
  - The predicted ullage and wall temperatures indicate an underprediction of heat transfer when compared to the experimental final ullage and wall temperatures.
- The turbulent cases overpredicted the pressurant required by 50%, however when turbulence damping at the interface was included using the default settings, the model predicted the required pressurant to within 1%.
  - The predicted ullage and wall temperatures indicate better agreement with the experimental final ullage and wall temperatures.
- More work is required to better understand and capture the damping that occurs at the liquid/vapor interface.
- For the case with sloshing, the preliminary ANSYS FLUENT CFD laminar model predicts the pressurant and liquid outlet temperature to be in a good agreement with the experimental measurements.
  - More work is required to overcome the numerical challenges associated with sloshing with phase change.