



A Computational Study of the Effect of Fill Level during Tank Self-Pressurization and Validation Against Ground-Based K-Site Experiment

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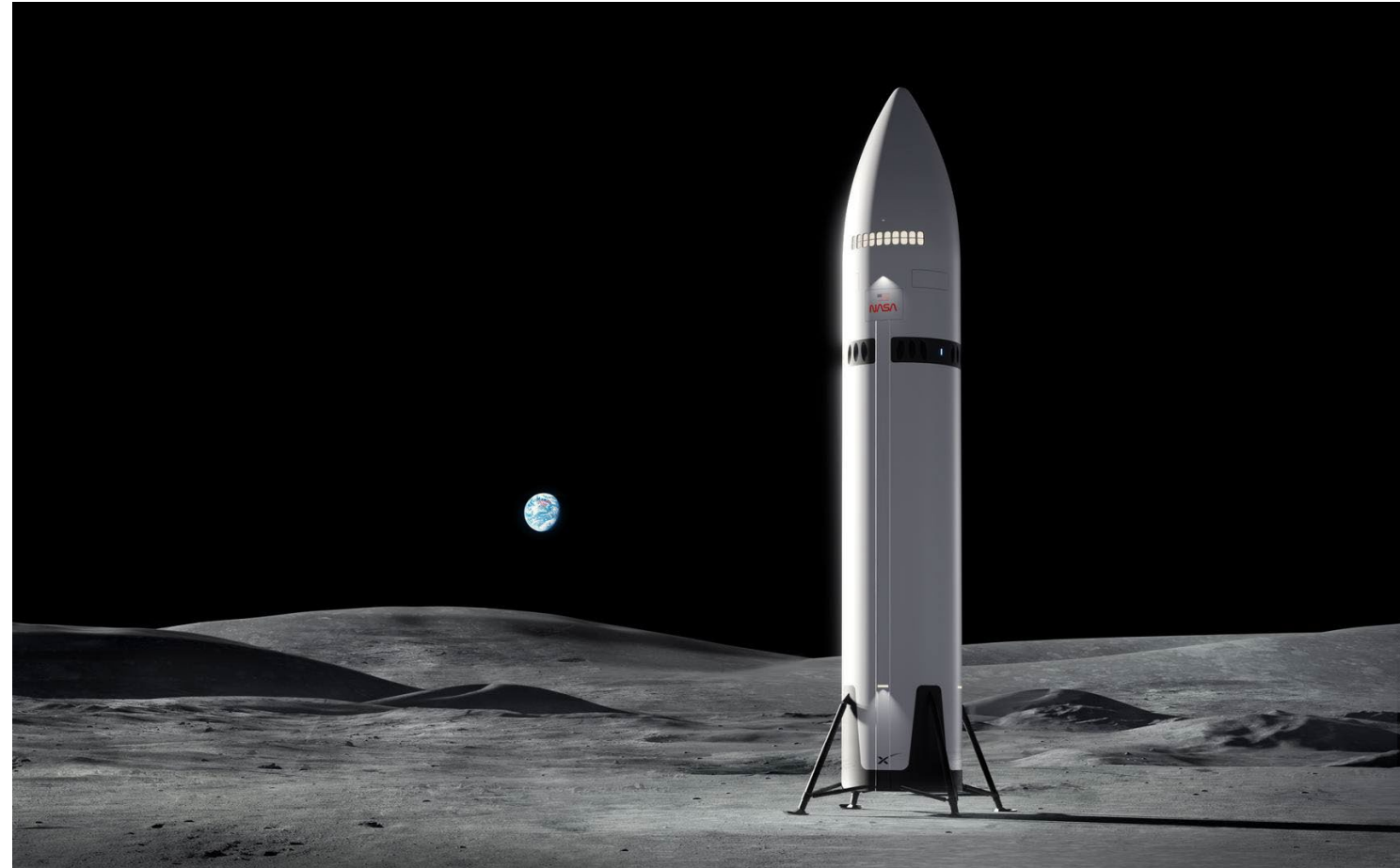
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Motivation



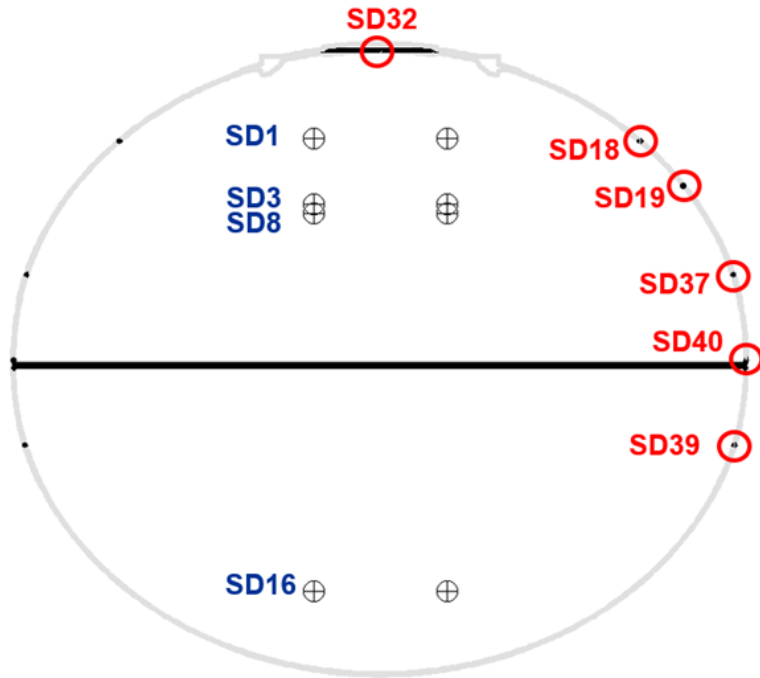
- Predicting rates of tank pressure increase when heat leaks into a cryogenic storage tank through insulation, structural support and tank penetrations is important for NASA's short and long duration missions.
- When heat is added to a cryogenic tank it causes an increase in liquid and vapor temperatures, evaporation of the liquid at the interface and an increase in tank pressure. This process is referred to as tank "self-pressurization".
- It is important to be able to accurately predict tank pressure and temperature increases during tank self-pressurization to design future rocket fuel tanks
- To be reliable CFD models must be validated against existing 1g and microgravity data



Artist's concepts show SpaceX's Starship Human Landing System (HLS) on the Moon

Photo courtesy: SpaceX

Case description



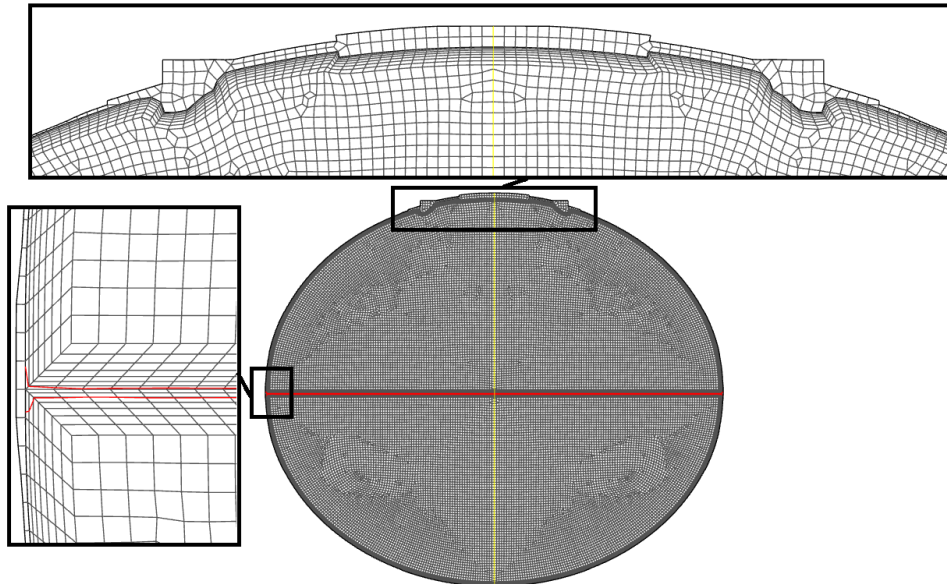
Experiment

- Testing conducted at the K-Site facility.
- Tank ellipsoidal volume of revolution with a major to minor axis ratio of 1.2 a major diameter of 2.2 m and a volume of 4.89 m³.
- Liquid hydrogen and its vapor fill the tank.
- Temperature sensors in the fluid and on the tank wall.
- Boil off test was conducted to determine the total heat leak rate into the tank.

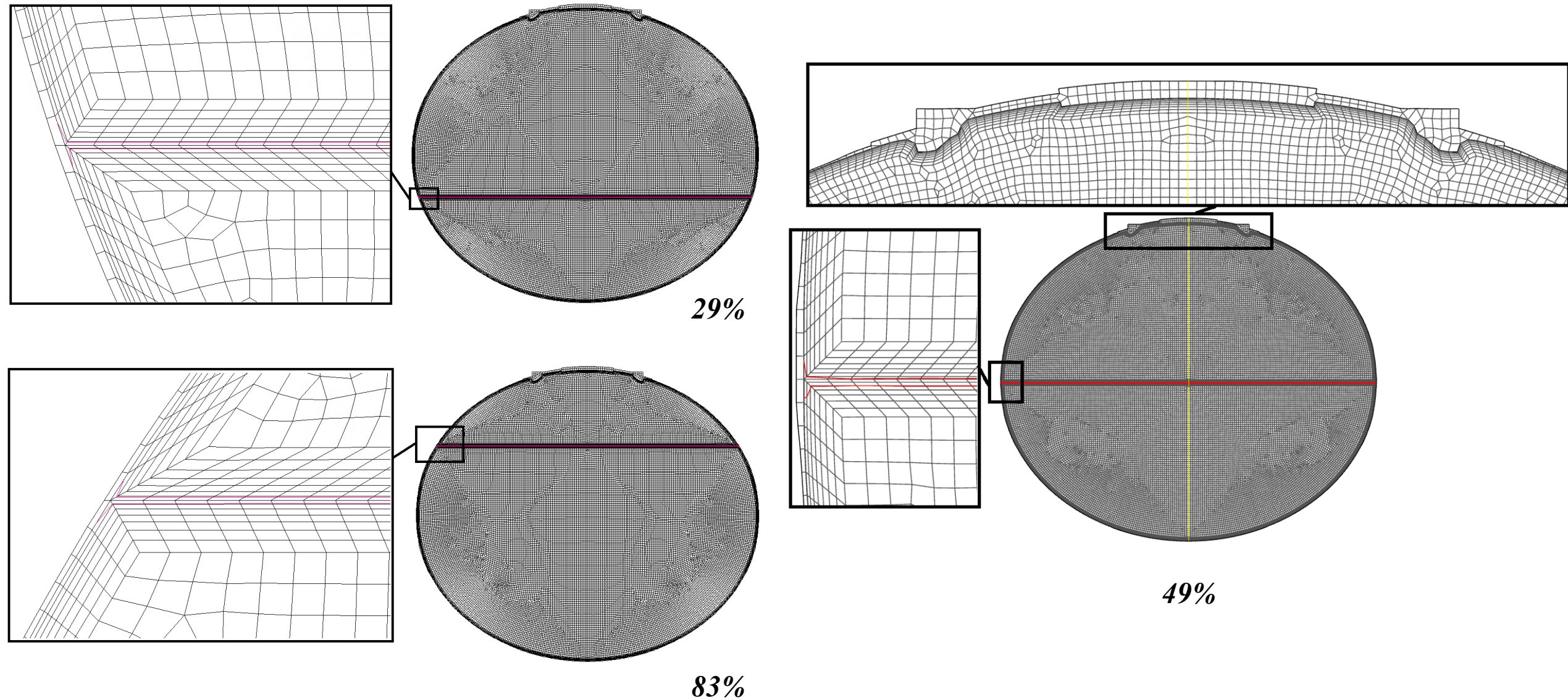
Hasan, M. M., Lin, C. S., Van Dresar, N. T., "Self-Pressurization of a Flightweight Liquid Hydrogen Storage Tank Subjected to Low Heat Flux," NASA TM-103804, 1991

CFD

- 2D axisymmetric geometry with tank wall included
- VOF Model
- $P_{init} = 103,000.0 \text{ Pa}$; T_{init} (at the interface and in the liquid) = T_{sat} (P_{init}) = 20.327 K; experimental vapor T profile used as initial conditions
- Temperature dependent fluid and solid properties
- CFD results for 49% fill level were presented this year at AIAA SciTech conference. CFD results for 29%, 83% fill levels presented and discussed here
- Two different heat flux values applied on the outside of the tank wall as B.C. – 2 and 3.5 W/m²



Case description – Computational meshes



Computational Model: Equations Solved



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

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

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

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

where σ – accommodation coefficient (value of 0.001 was used)
 M – molar mass of hydrogen
 R – universal gas constant (8.314472 J/mol K)
 P_i and P_v – interfacial and vapor pressures, Pa
 T_i and T_v – interfacial and vapor temperatures, K (assumed that $T_i = T_v \cong T_{sat}$ at the interface)

Computational Model: Equations Solved



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

Continuity of Volume Fraction of the q -th phase:
$$\frac{1}{\rho_q} \left[\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) \right] = S_{\alpha_q}$$

Continuum Surface Force (Brackbill et al.):
$$F_{vol} = \sum_{\text{pairs } ij, i < j} \sigma_{ij} \frac{\alpha_i \rho_i h_j \nabla \alpha_j + \alpha_j \rho_j h_i \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)}$$

where $h_i = \nabla \cdot \hat{n}$

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

UDFs used:

VOF (DEFINE_MASS_TRANSFER)

- ❖ Calculate mass transfer using Schrage relation and supply it to Fluent for phase interaction at the interface

Computational Model: Numerical Methods



- Simulations performed using ANSYS Fluent version 24.1
- **2D axisymmetric** geometry was modeled
- Compressible ideal gas
- Surface tension effects via Continuum Surface Force method of Brackbill et al.
- Contact angle 0°
- Wagner equation used for calculating saturation conditions

Turbulence models:

- The Shear Stress Transport $k-\omega$ model of Menter (kw-SST) used with Turbulence Damping (TD=100) at the interface
 - Improved Delayed Detached Eddy Simulation (IDDES) model proposed by Shur and Gritskevich
 - Laminar simulations (without any turbulence modeling) were also performed
-
- Second Order Upwind scheme was used for discretization of the Energy, Momentum and Turbulence equations (cell values)
 - PISO scheme was used for the Pressure-Velocity coupling (cell values)
 - Least Squares Cell Based scheme was used for the gradient calculations (face values)
 - Body Force Weighted scheme was used for the Pressure interpolation (face values)
 - Point Implicit (Gauss-Seidel) linear equation solver with Algebraic Multi-Grid (AMG) method was used for solving linearized systems of equations
 - Bounded Second Order Implicit temporal discretization was used with implicit VOF model with $\Delta t = 0.05$ s

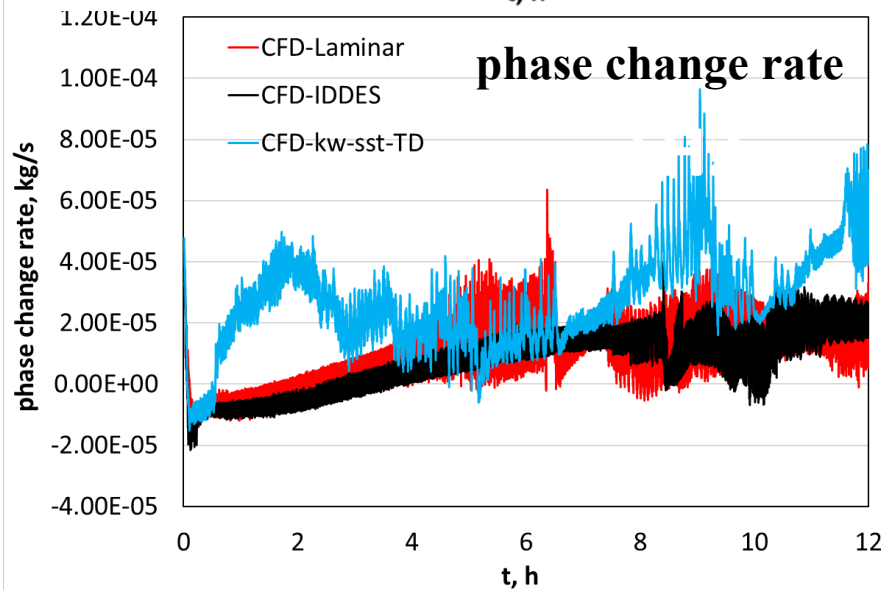
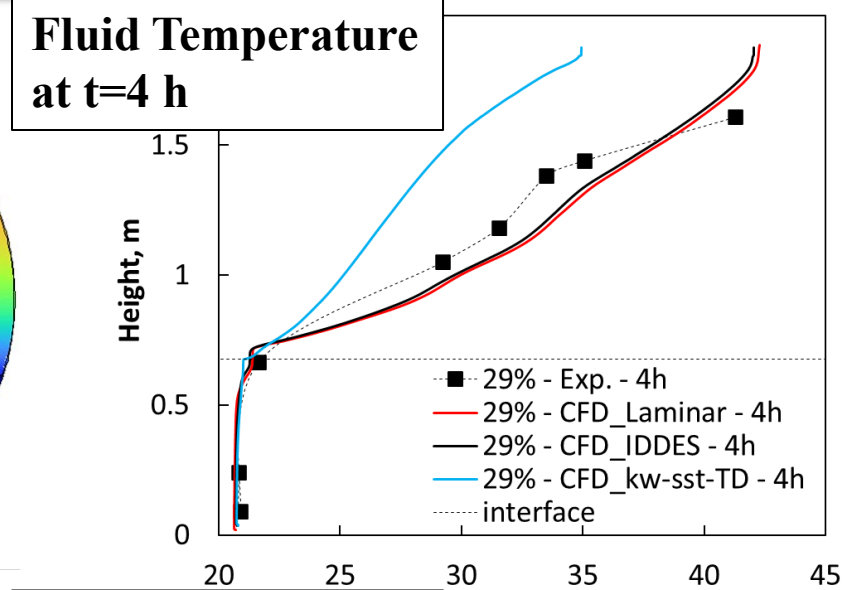
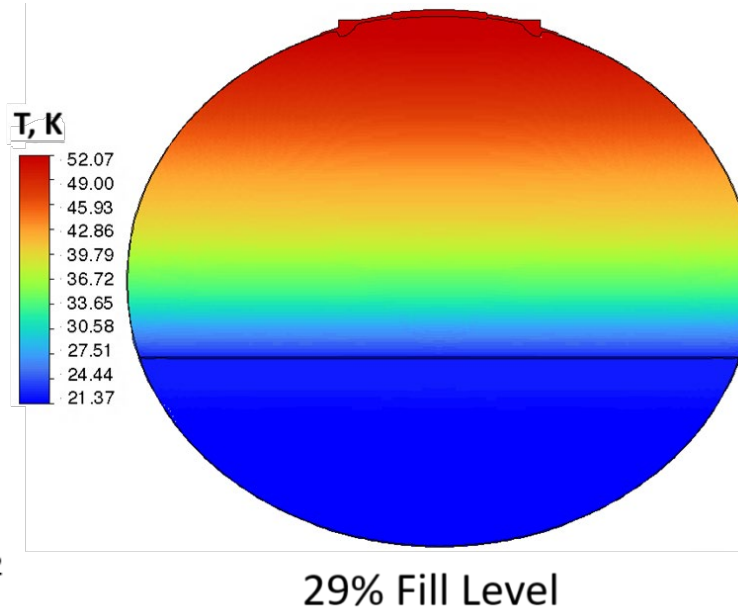
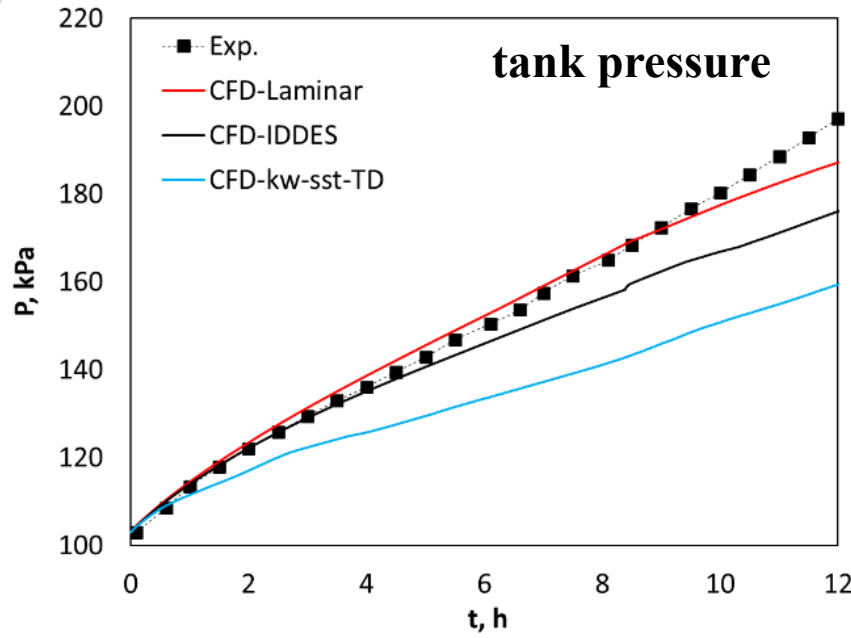
□ 3.5 W/m^2

- The effect of **Turbulence Modeling**
 - 29 % fill level
 - 49% fill level
 - 83% fill level
- The effect of **Fill Level**
- The effect of **Heat Leak** at different fill levels

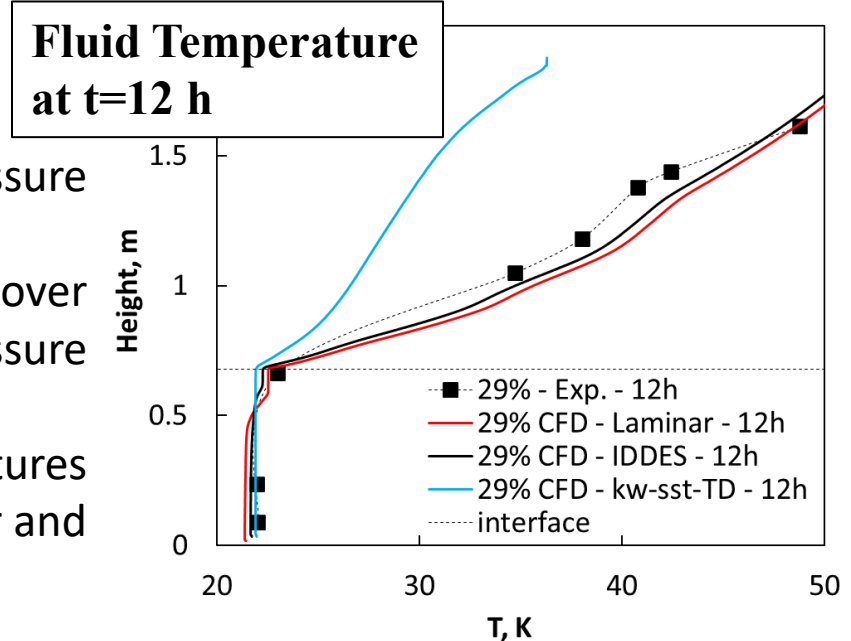
□ 2 W/m^2

- The effect of **Fill Level** and **Heat Leak**

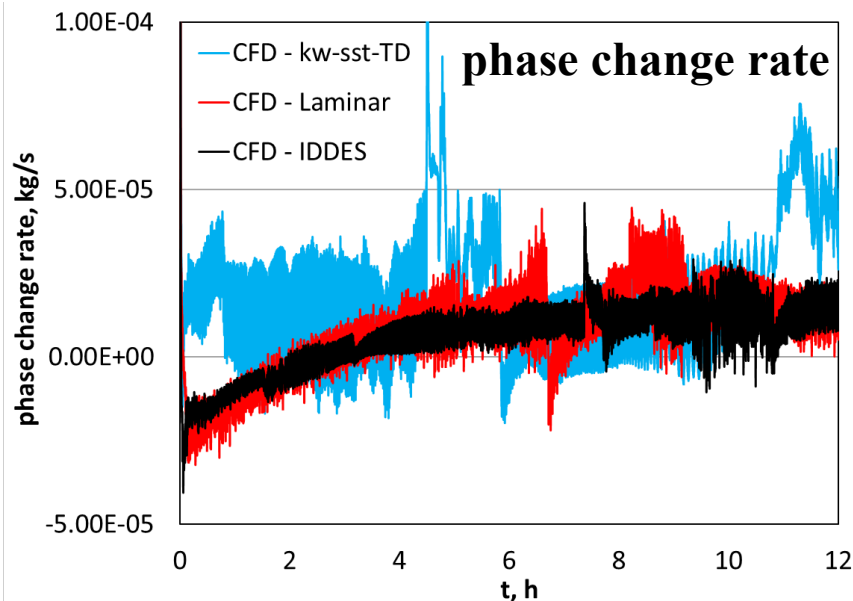
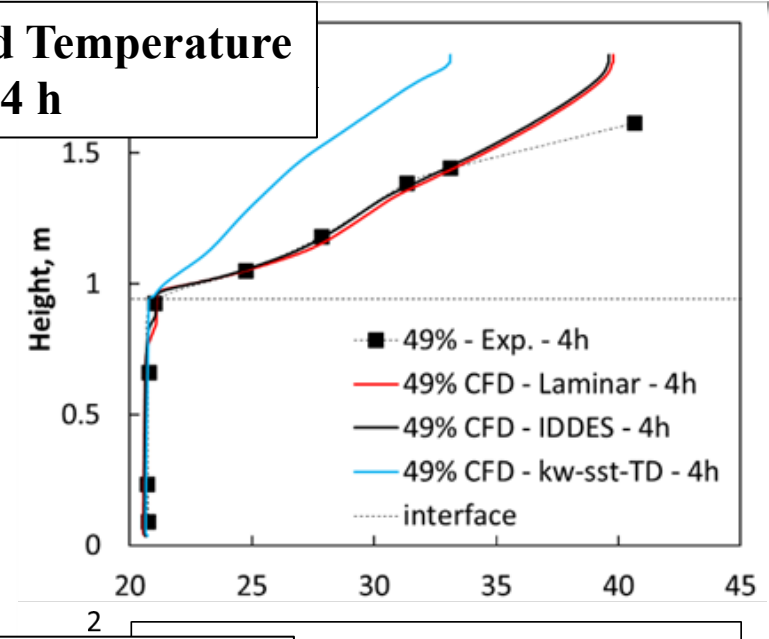
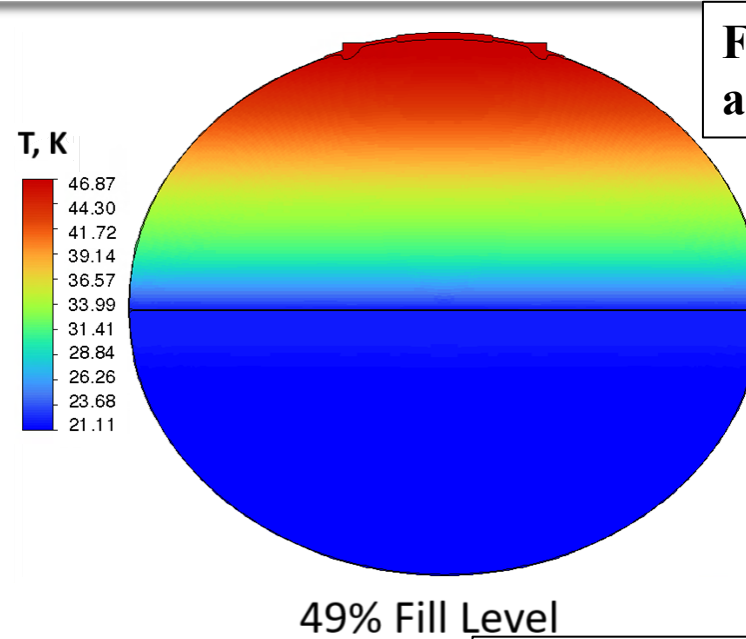
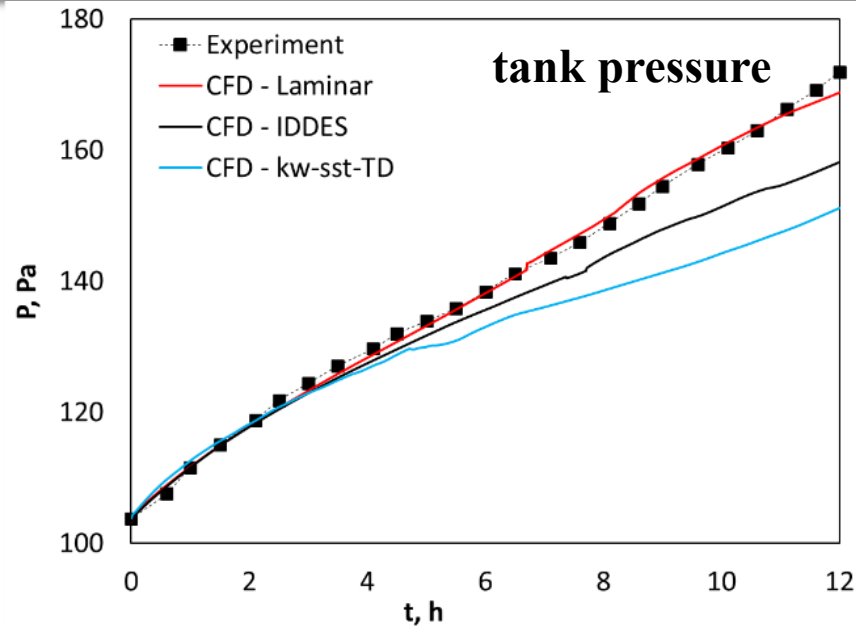
CFD Results: 29% fill level – effect of turbulence modeling



- **Laminar** – best tank pressure prediction
- **IDDES** – significant improvement over **RANS** for predicting tank pressure and temperatures
- Tank pressure and fluid temperatures are well predicted by the Laminar and IDDES models

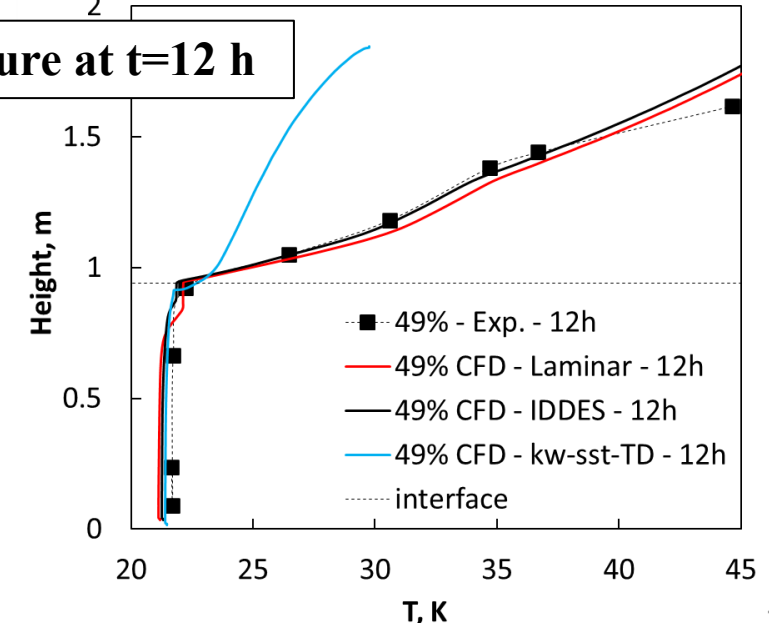


CFD Results: 49% fill level – effect of turbulence modeling

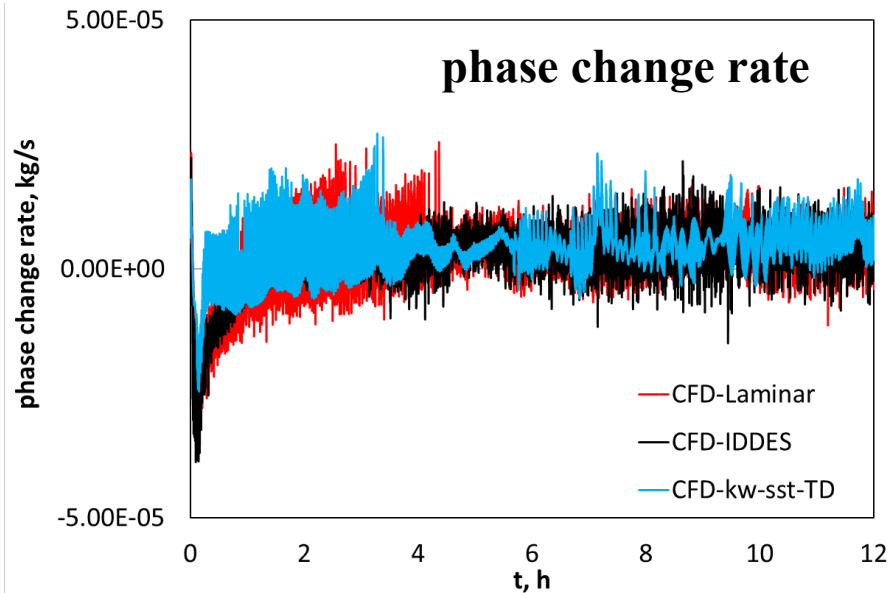
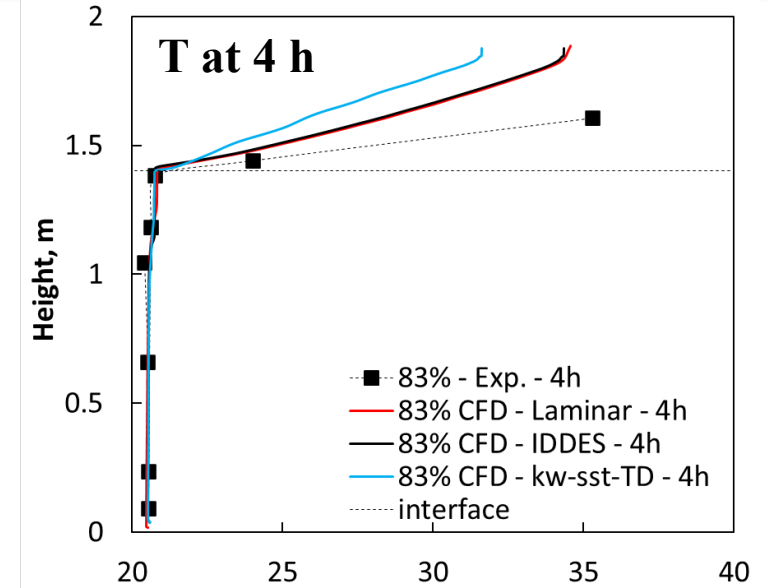
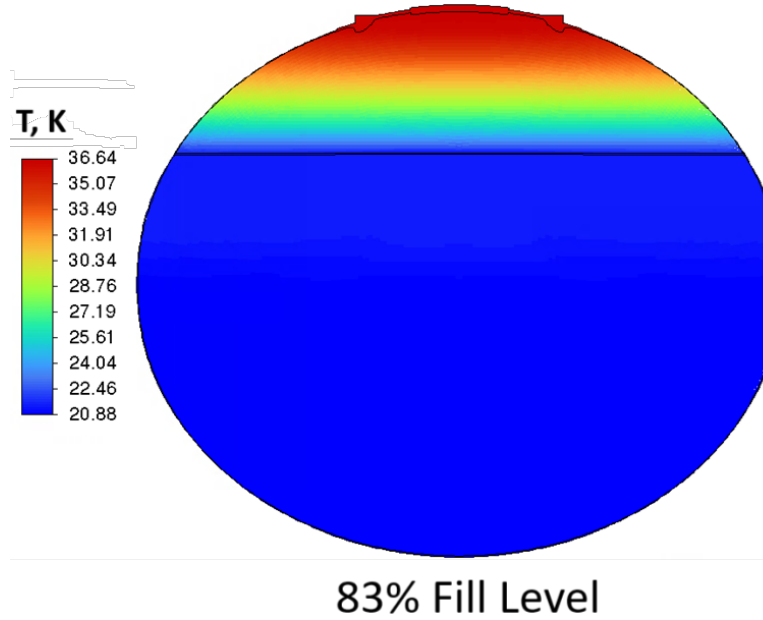
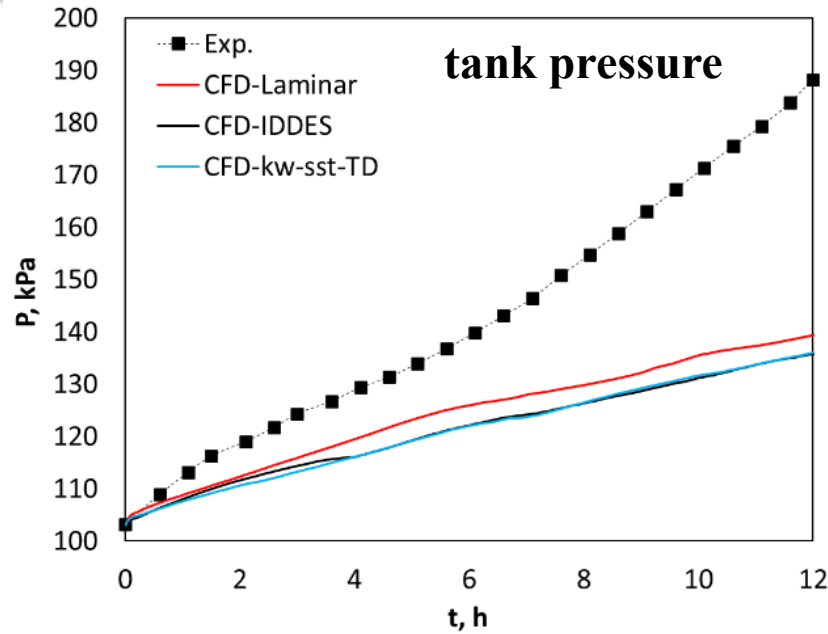


- **Laminar** – best tank pressure prediction
- **IDDES** – significant improvement over **RANS** for predicting tank pressure and temperatures. **Same as in 29 % fill level.**
- Tank pressure and fluid temperatures are well predicted by the Laminar and IDDES models

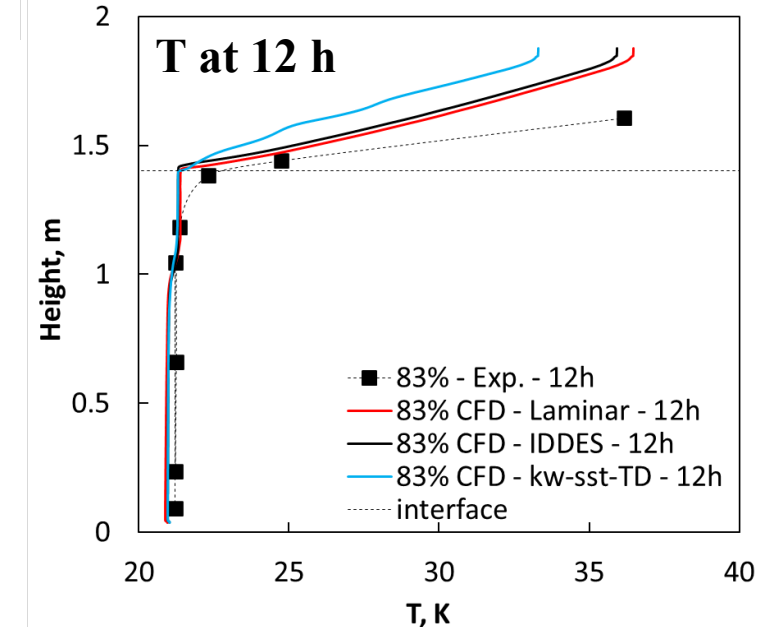
Fluid Temperature at $t=12 \text{ h}$



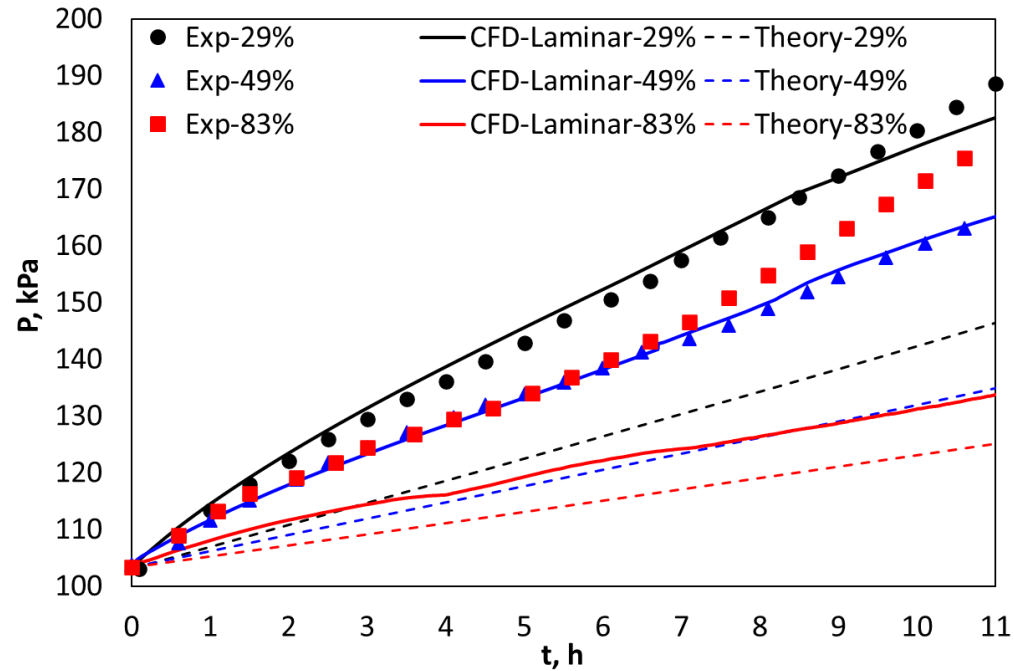
CFD Results: 83% fill level – effect of turbulence modeling



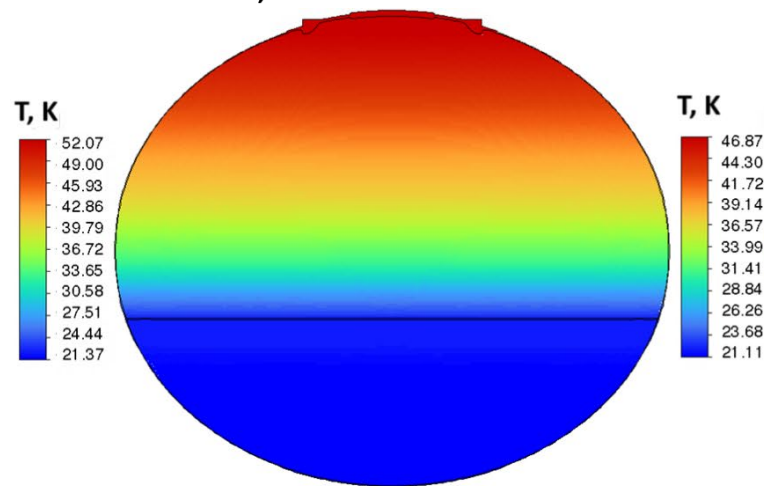
Tank pressure and fluid temperatures are under predicted by the **Laminar**, **IDDES** and **RANS** models.



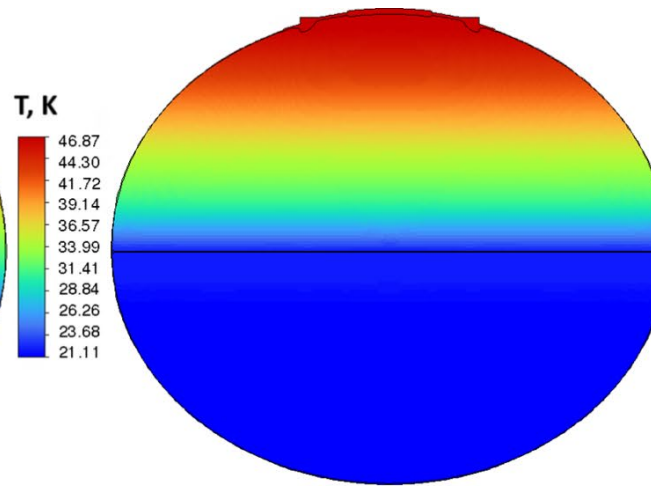
CFD Results – Fill Level Effect



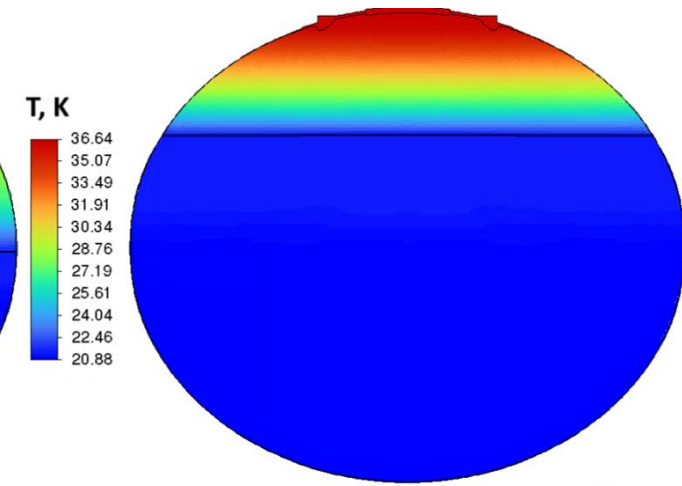
- Experimental data follows theoretical trend for 29% and 49% fill levels, but not for the 83% fill level
- CFD results follow theoretical trend for all three fill levels
- CFD predicts tank pressure well for 29% and 49% fill levels, but significantly under-predicts for the 83% fill level



29% Fill Level



49% Fill Level



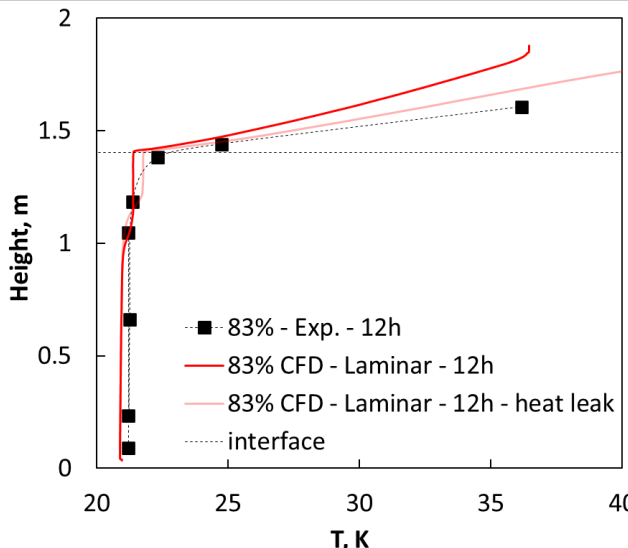
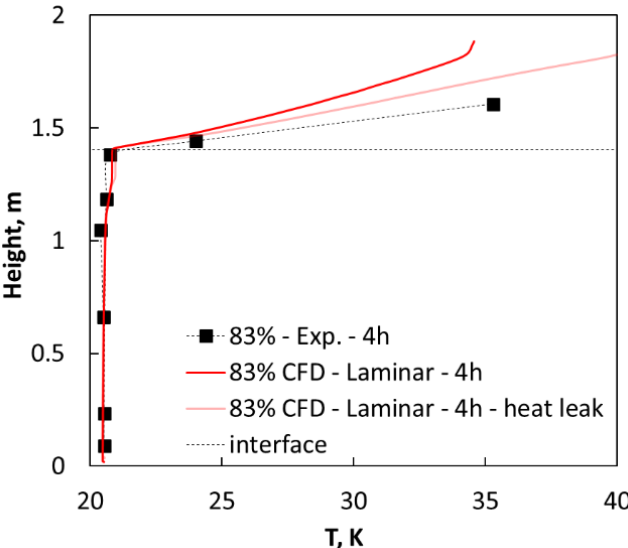
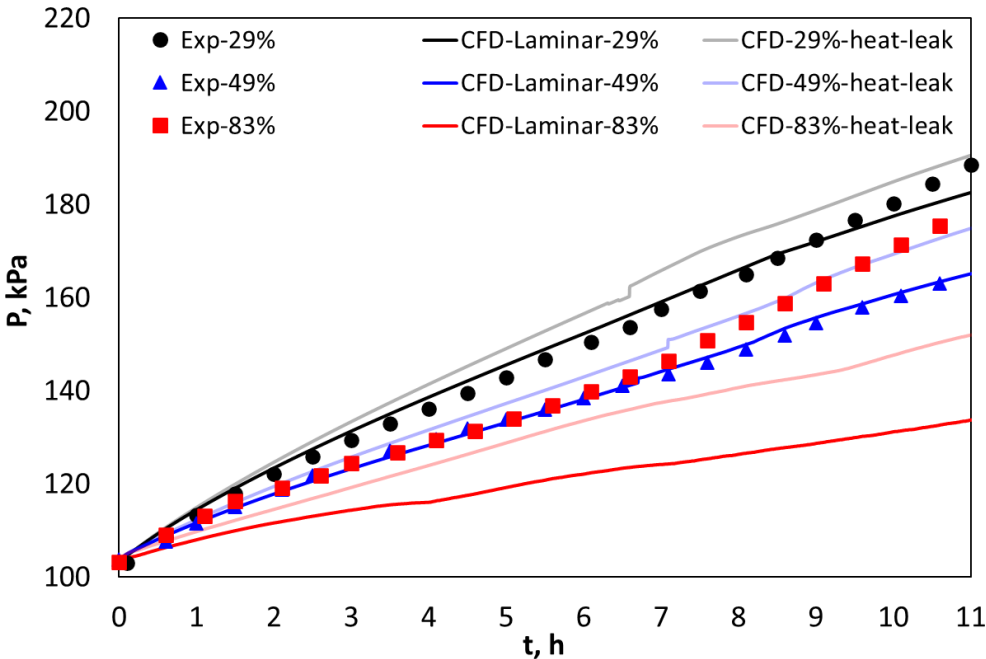
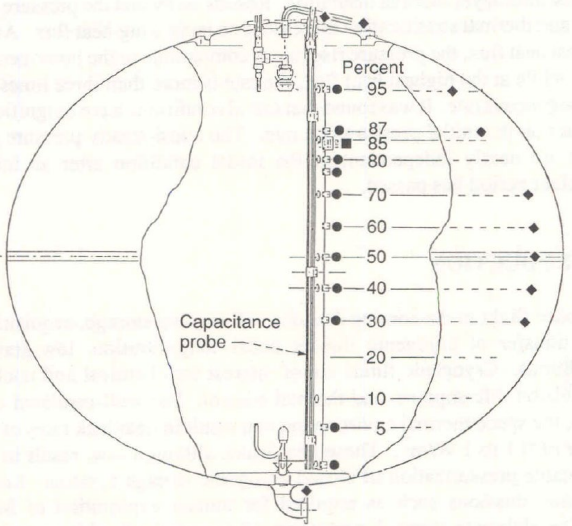
83% Fill Level

CFD Results – Heat Leak at different Fill Levels



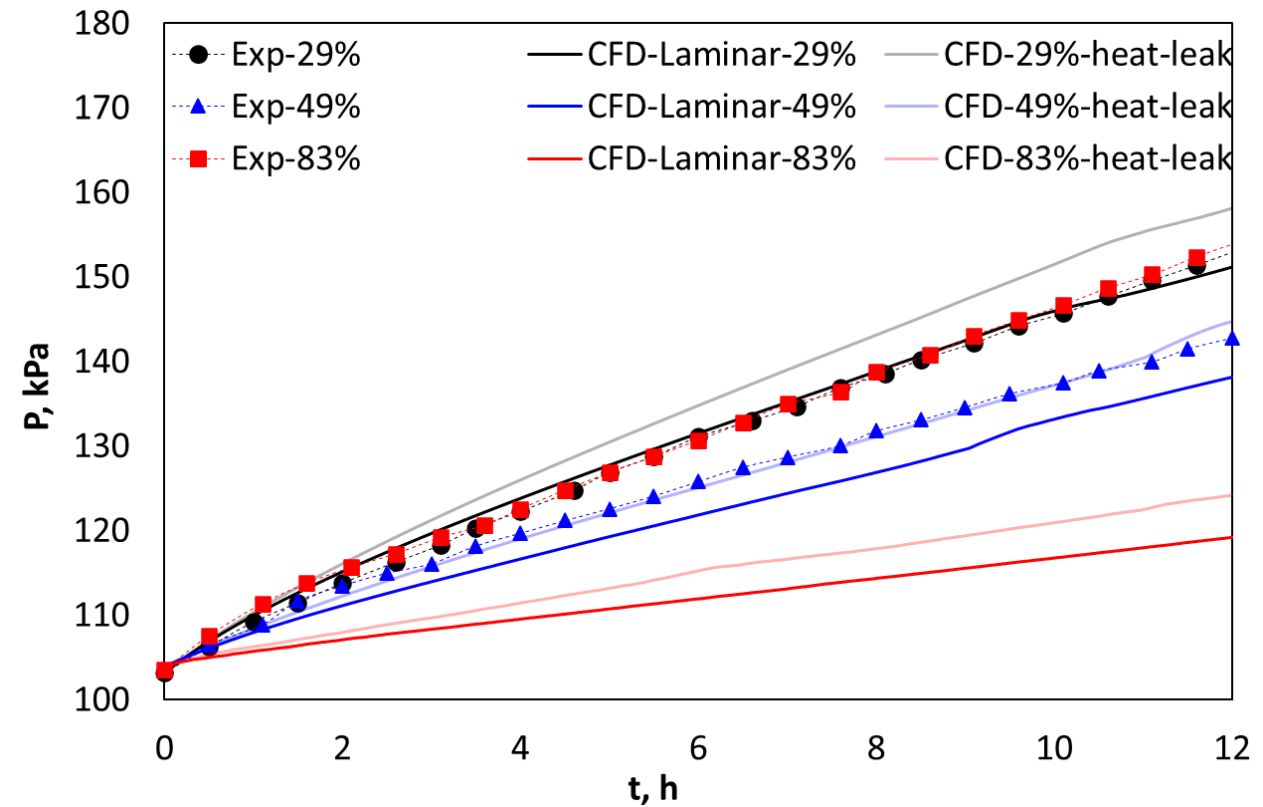
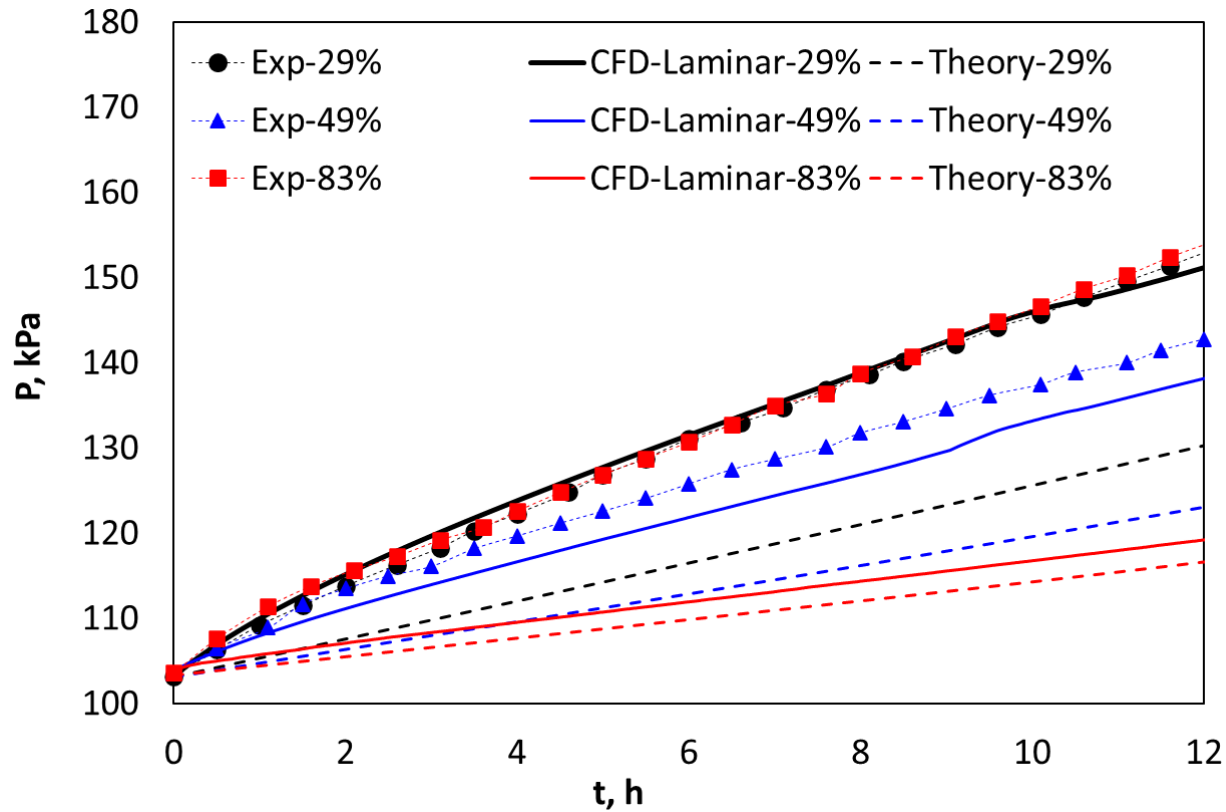
TABLE 2. - SUMMARY OF HEAT TRANSFER RESULTS

	Shroud temperatures °R			
	530		630	152
	This report	From TN D-8282		
	Chamber vacuum - torr			
	4.0×10^{-6}	1.7×10^{-5}	4.0×10^{-6}	2.0×10^{-5}
Steady state heat transfer rate				
Measured total heat input, BTU/hr	95.8	76.9	164.6	15.9
Noninsulation heat transfer, BTU/hr				
* Support struts	6.8	6.8	9.6	0.5
* Plumbing/ducts	7.8	3.0	10.9	1.3
* Electrical wires	2.1	1.3	3.0	0.2
* Sum	16.7	11.1	23.5	2.0
Heat transfer through insulation, BTU/hr	79.1	65.8	141.1	13.9
Insulation heat flux, BTU/hr-ft	0.527	0.439	0.941	0.093



Stochl, R. J., Knoll, R. H., "Thermal Performance of a Liquid Hydrogen Tank Multilayer Insulation System at Warm Boundary Temperatures of 630, 530 and 152 °R," NASA TM-104476, 1991

CFD Results – 2 W/m²



Similar to the high heat flux case:

- Experimental data follows theoretical trend for 29% and 49% fill levels, but not for the 83% fill level
- CFD results follow theoretical trend for all three fill levels
- CFD predicts tank pressure well for 29% and 49% fill levels, but significantly under-predicts for the 83% fill level
- Including heat leak improves results for the 83% fill level case, but only marginally

Conclusions:



- CFD model was developed and validated against K-Site LH2 tank self-pressurization experimental data collected in normal gravity for 29 %, 49 % and 83% fill levels with 2 and 3.5 W/m² wall heat fluxes.
- The **Laminar** VOF model overall is in the **best agreement** with the experimental data for all fill levels, followed by the RANS-LES blended **IDDES** turbulence model, which shows improvements over the **RANS** turbulence model in predicting tank pressure and fluid temperatures.
- The **Laminar** VOF predicted tank pressures are within 3% of the measured ones for 29 % and 49 % fill level cases, however, tank pressures are significantly under-predicted up to 25% for the 83% fill level case with the higher heat flux case of 3.5 W/m². Similar trend is observed for the lower heat flux case of 2 W/m².
- When heat leak into the tank (as reported by Stochl) was included in CFD in the high heat flux case, predicted tank pressure and temperatures improved, but tank pressure was still 15% under-predicted by the Laminar VOF model.



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