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Modeling Self-Pressurization and Spray Bar Pressure Control of a Cryogenic Storage Tank in Normal Gravity

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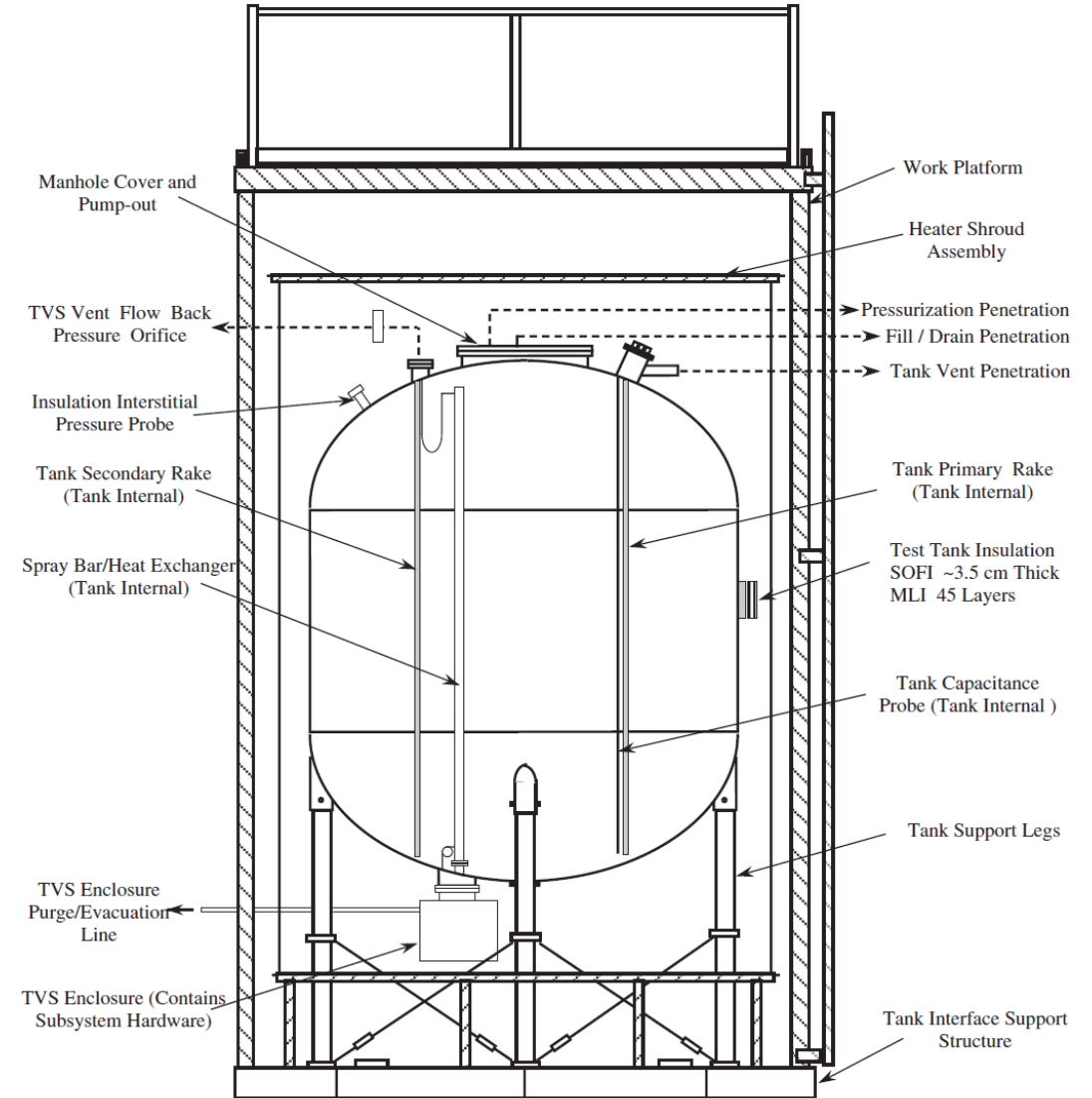
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- Long-duration space missions demand reliable cryogenic fluid management to reduce mass and losses.
- Traditional venting methods add weight, complexity, and propellant waste over time.
- The spray-bar Thermodynamic Vent System (TVS) controls tank pressure, reducing boil-off and venting.
- Ground-based tests conducted at NASA MSFC with the Multipurpose Hydrogen Test Bed (MHTB) tank provide valuable data for validating CFD models.
- CFD modeling of cryogenic systems enables the predictive capabilities needed to support advanced space exploration.

EXPERIMENTAL SETUP

- **MHTB Tank:**
 - Tank Volume: 18 [m³] (693 [ft³])
 - Tank Height: 3.05 [m] (10 [ft])
 - Tank Diameter: 3.05 [m] (10 [ft])
 - 2:1 elliptical domes
 - Representative in size and shape of a fully integrated LH₂ propellant tank
 - Accommodated various CFM concepts
-
- **Experiment:**
 - Self-pressurization
 - TVS pressure control



Continuity:

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

Momentum:

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

Energy:

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

Schrage's Relation:

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

where

σ – accommodation coefficient (value of 0.001 was used)

M – molar mass of hydrogen

R – universal gas constant (8.314 [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)

Continuity of Volume Fraction for qth phase:

$$\frac{1}{\rho_q} \left[\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}_q) \right] = S_{\alpha_q} \quad \sum_{q=1}^n \alpha_q = 1$$

Properties:

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

Energy and Temperature are defined as mass average scalars:

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

Interfacial mass transfer per unit volume:

$$S_{\alpha_q} = \dot{m}_i \cdot A_i$$

$\dot{m}_i$ - mass flux vector [kg/(m²·sec)]

A_i - interfacial area density [1/m]

α - volume fraction of the primary phase

$$A_i = |\nabla \alpha|$$

Surface Tension at the interface (Volume Force):

$$\mathbf{F}_{vl} = \sum_{\text{pairs } ij, i < j} \sigma_{ij} \frac{\alpha_i \rho_i h_i \nabla \alpha_j + \alpha_j \rho_j h_j \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)}$$

Surface Curvature:

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

Droplet Force Balance:

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}$$

Droplet Energy Equation:

$$m_p c_{p_p} \frac{dT_p}{dt} = h \cdot A_p (T_\infty - T_p) - L \dot{m}_p$$

Droplet Heat Transfer Coefficient Equation:

$$Nu = \frac{h d_p}{k_\infty} = 2.0 + 0.6 Re_d^{1/2} Pr^{1/3}$$

Relative Reynolds Number:

$$Re_d \equiv \frac{\rho d_p |\vec{u}_p - \vec{u}|}{\mu}$$

- Simulations performed in ANSYS Fluent version 24.1
- Mass transfer VOF model and the T-sat Model were integrated into a UDF
- Compressible ideal gas
- Surface tension effects via the Continuum Surface Force method
- Contact angle 0°

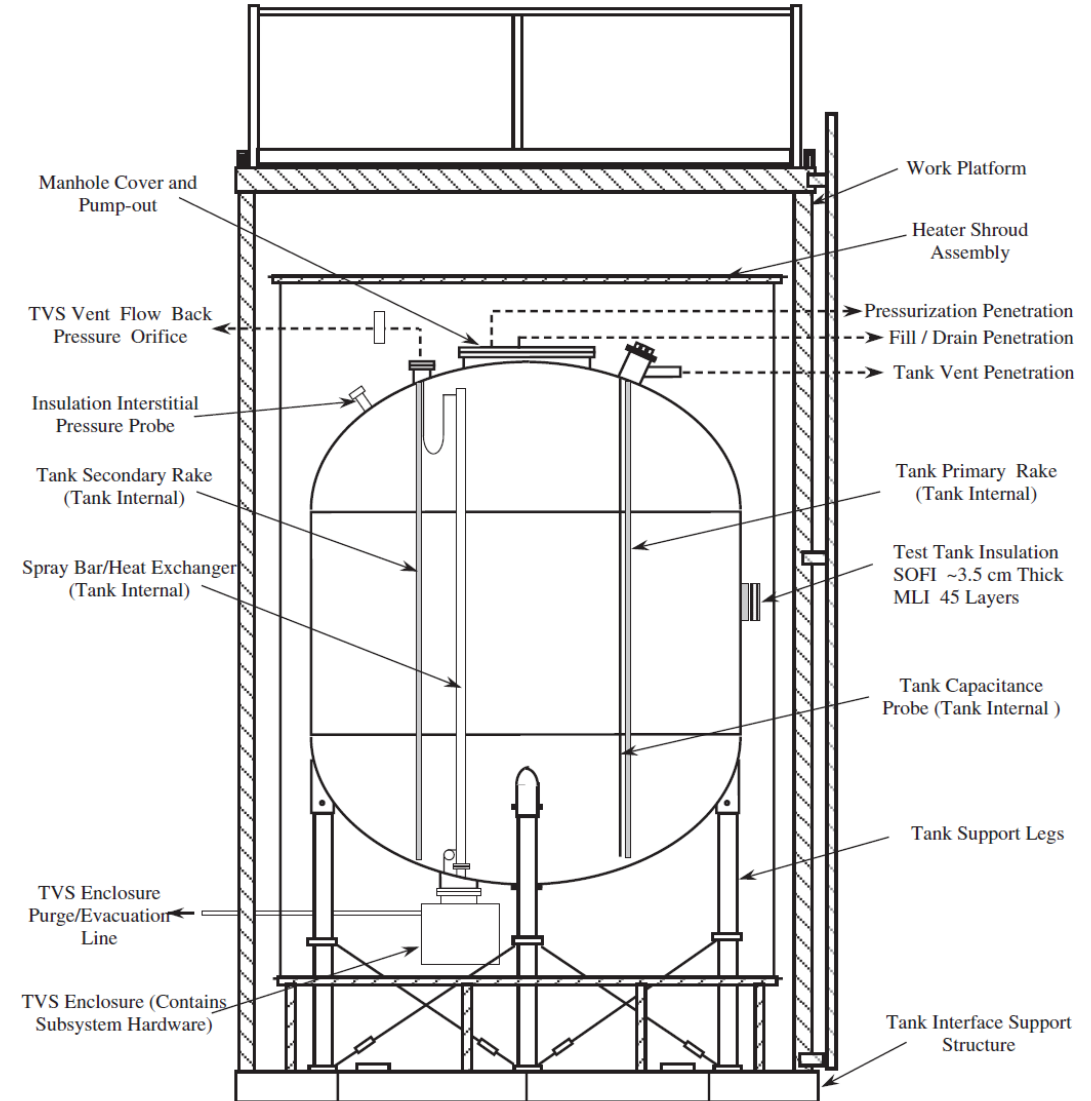
- **Second Order Upwind Scheme** – Energy, Momentum, and Turbulence Equations
- **Bounded Central Difference Method** – Scale-resolving methods
- **PISO Scheme** – Pressure-Velocity coupling
- **Least Squares Cell Based Scheme** – gradient calculations
- **Time step size**
 - Self-pressurization: 0.05s
 - Spray-bar Mixing: 0.001s

Experimental Conditions:

- 25% initial liquid fill volume (75% vapor volume)
- Initial Pressure: 122.1 kPa
- Final Pressure: 135.1 kPa
- Test Duration: 18.5 hours (66600 seconds)

CFD Setup:

- 2D Axisymmetric model
 - Except for the LES case
- Conduction through tank walls was not considered
- Previous multinode simulations determined heat flux boundary conditions

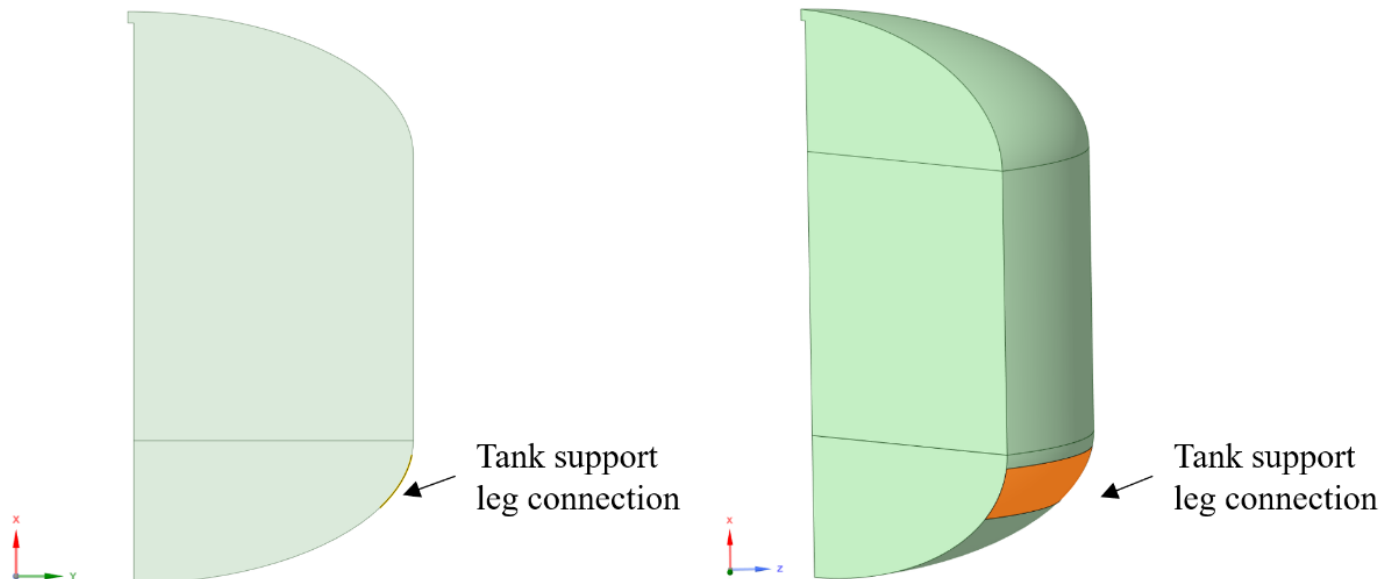


Turbulence Models:

- Laminar
- SST k- ω
- Stress Blended Eddy Simulation (SBES)
- Improved Delayed Detached Eddy Simulation (IDDES)
- Large Eddy Simulation (LES)

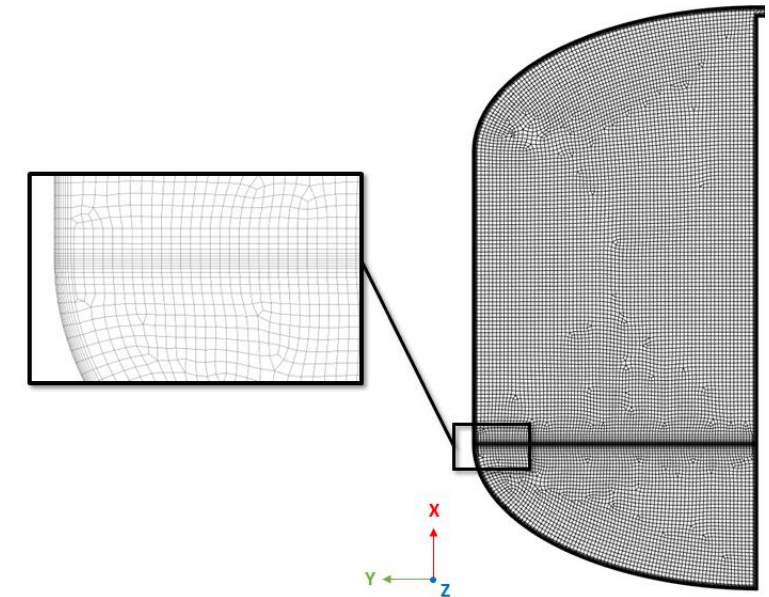
Heat Flux Boundary Conditions:

- **1.8 [W/m²]** applied to the tank support leg connection area
- **0.37 [W/m²]** applied to the rest of the tank



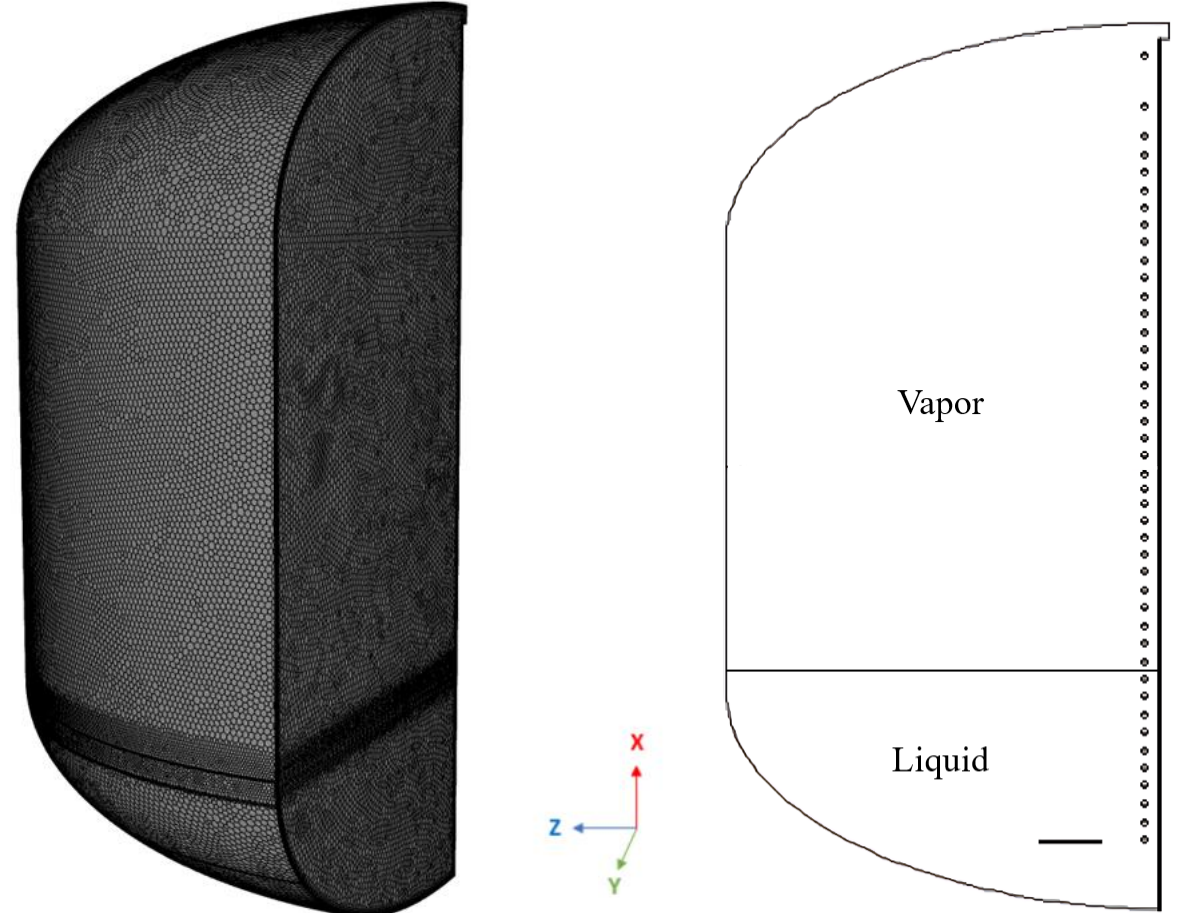
Computational Mesh:

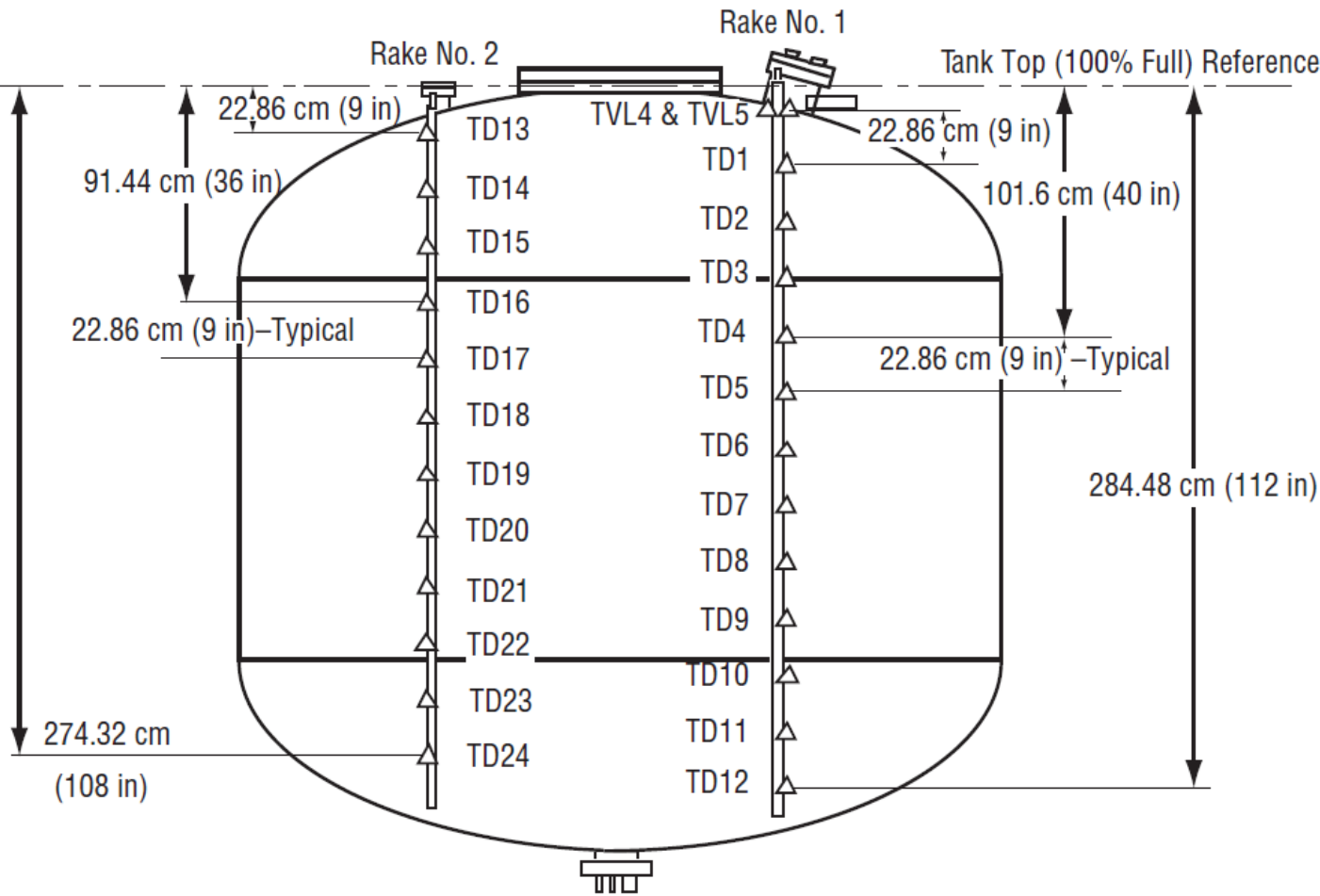
- 20 [mm] mesh size (15,690 cells)
- LES mesh – 1/8th sector of the entire tank
 - Polyhedral cells



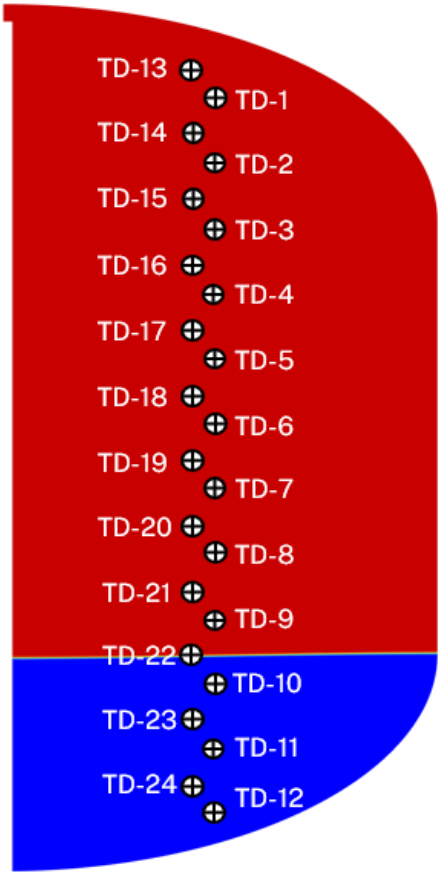
CFD Setup:

- Final self-pressurization results revolved around central-axis
- 33 Spray Injectors modeled as a discrete phase model (DPM) source
- Individual injector flow rate: 3.6×10^{-4} [kg/s]
- Spray liquid temperature: 21.11 [K]
- Laminar solution only considered

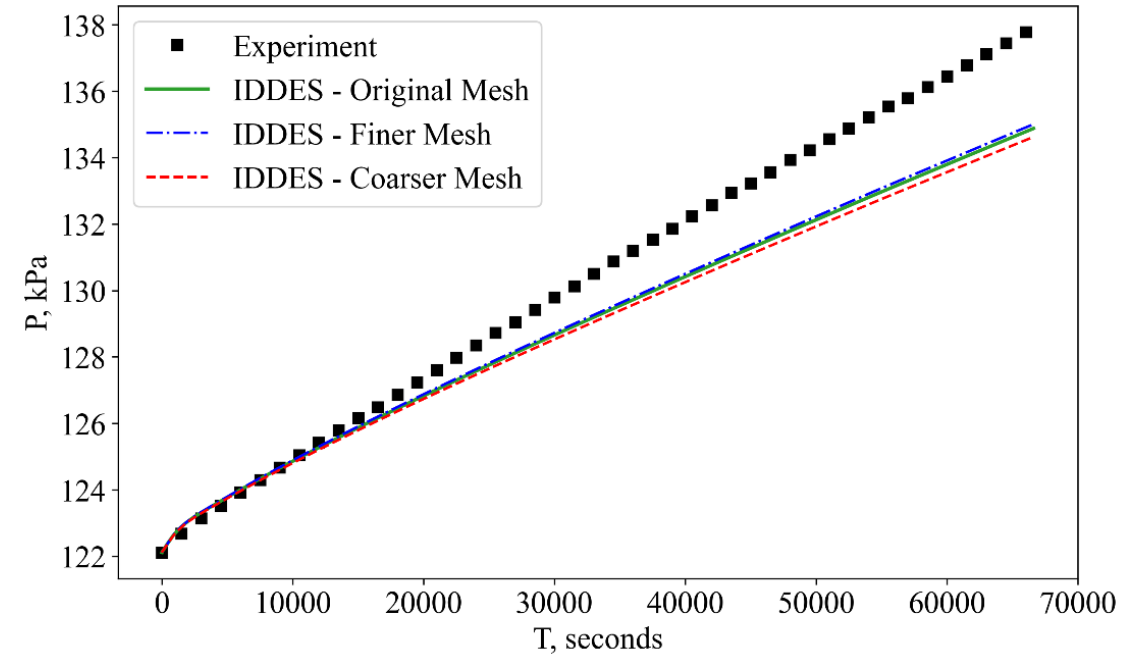
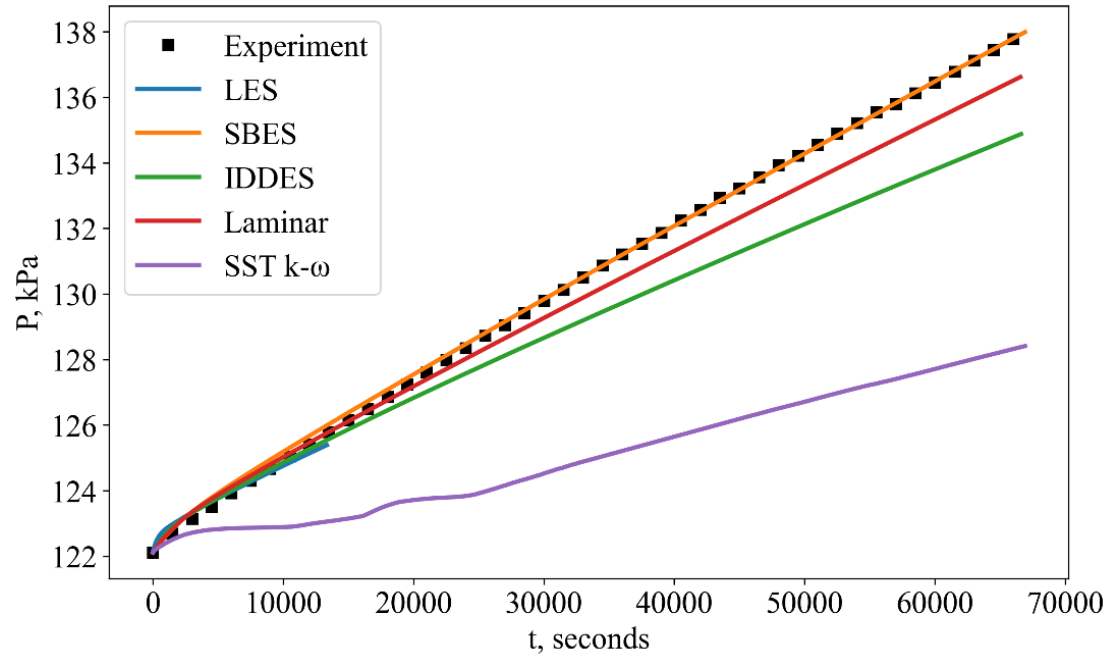




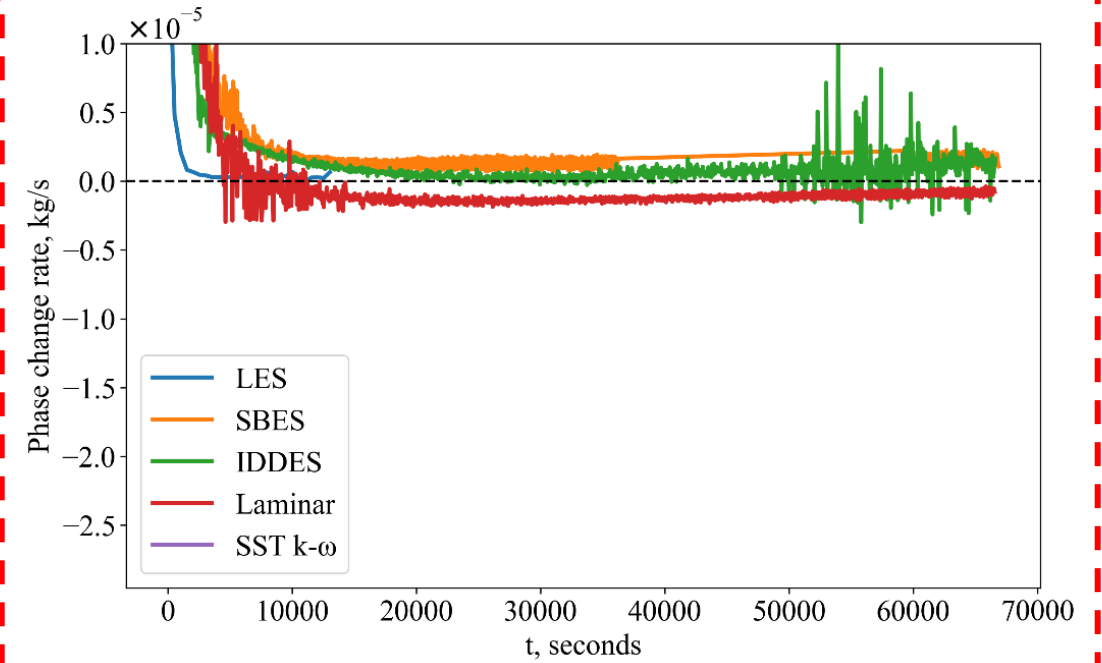
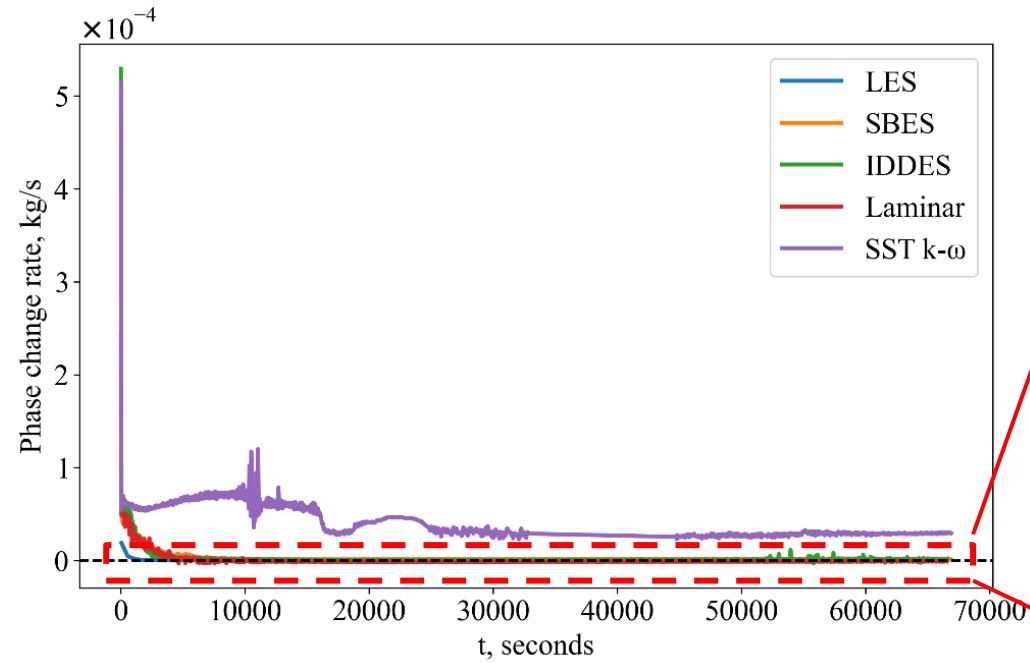
MHTB internal instrumentation rakes



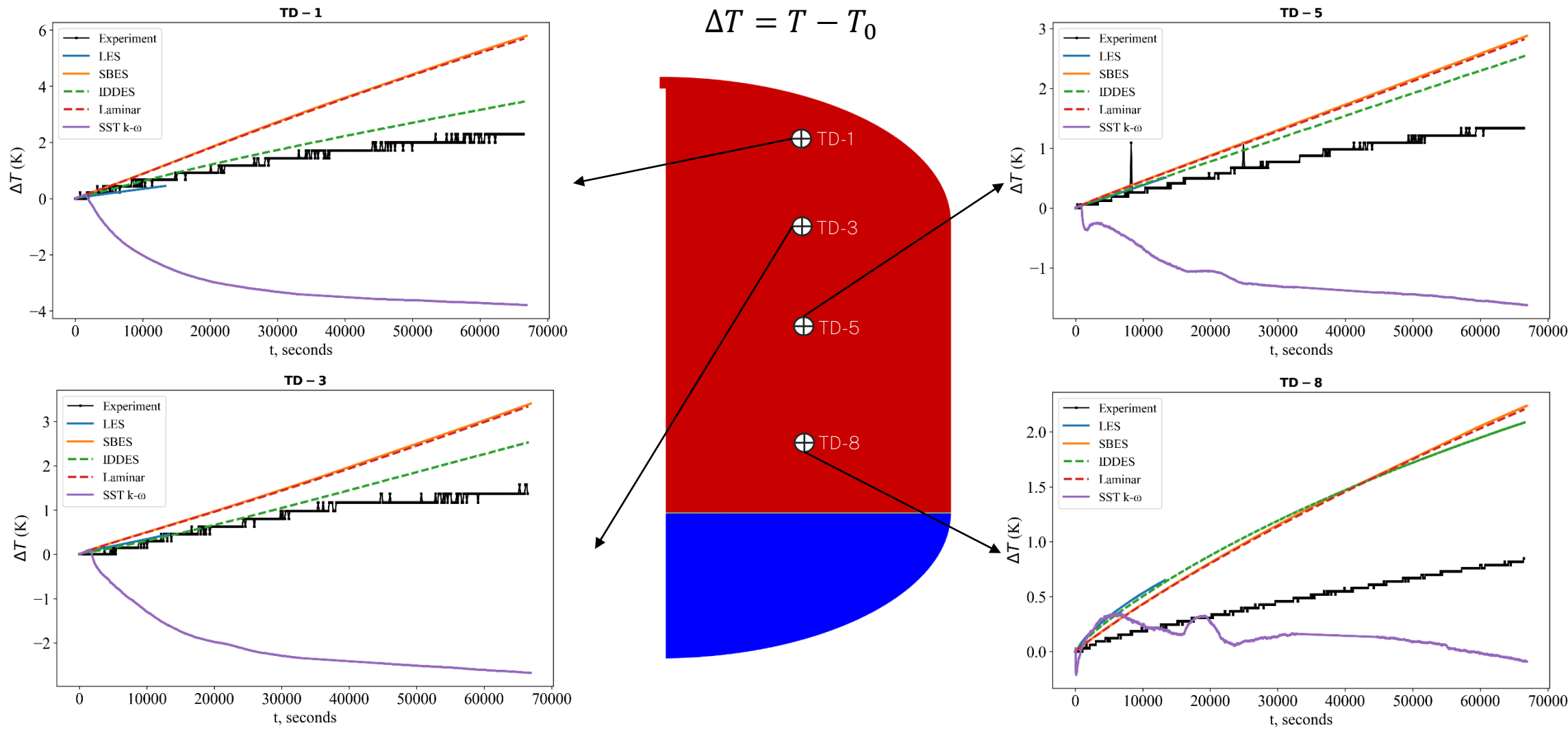
CFD temperature diodes

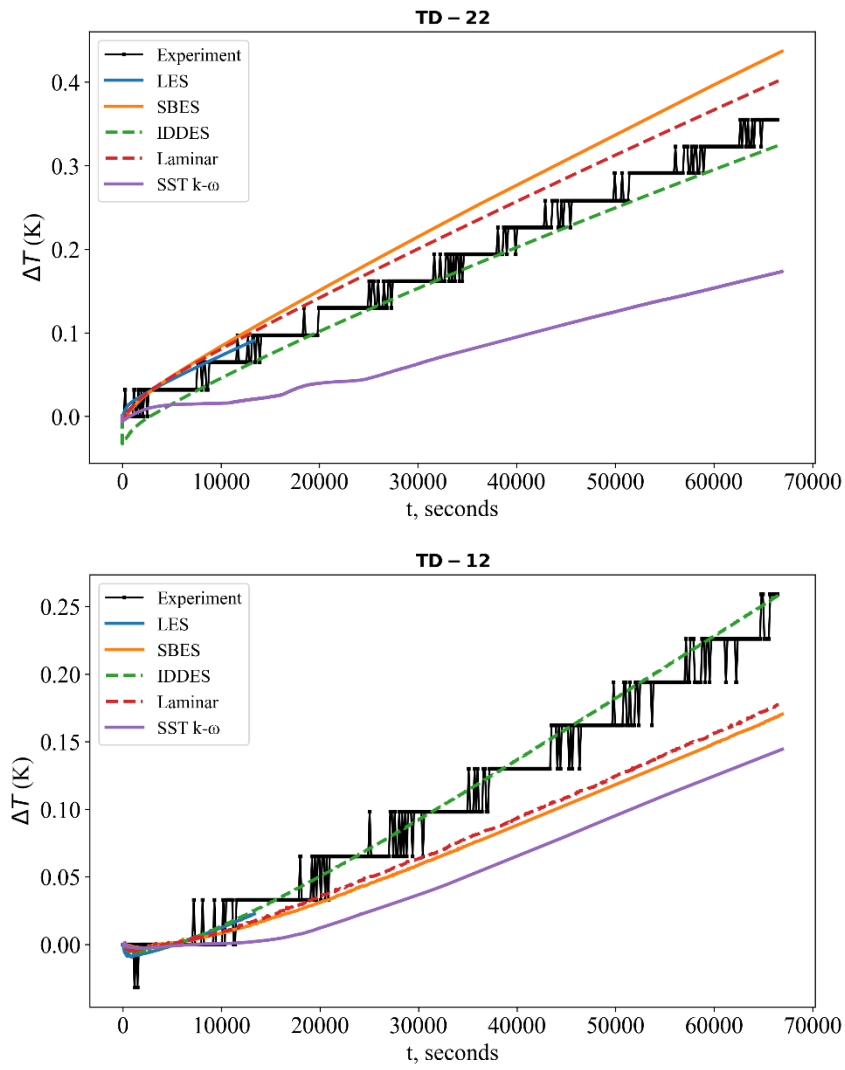


Coarse Mesh: average cell size 30 [mm] (8,857 cells)
Original Mesh: average cell size 20 [mm] (15,977 cells)
Finer Mesh: average cell size 10 [mm] (50,942 cells)

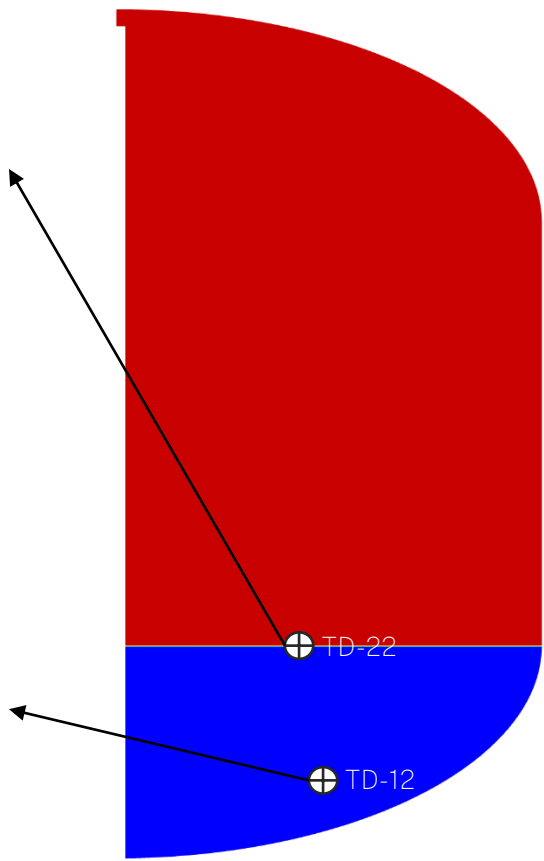


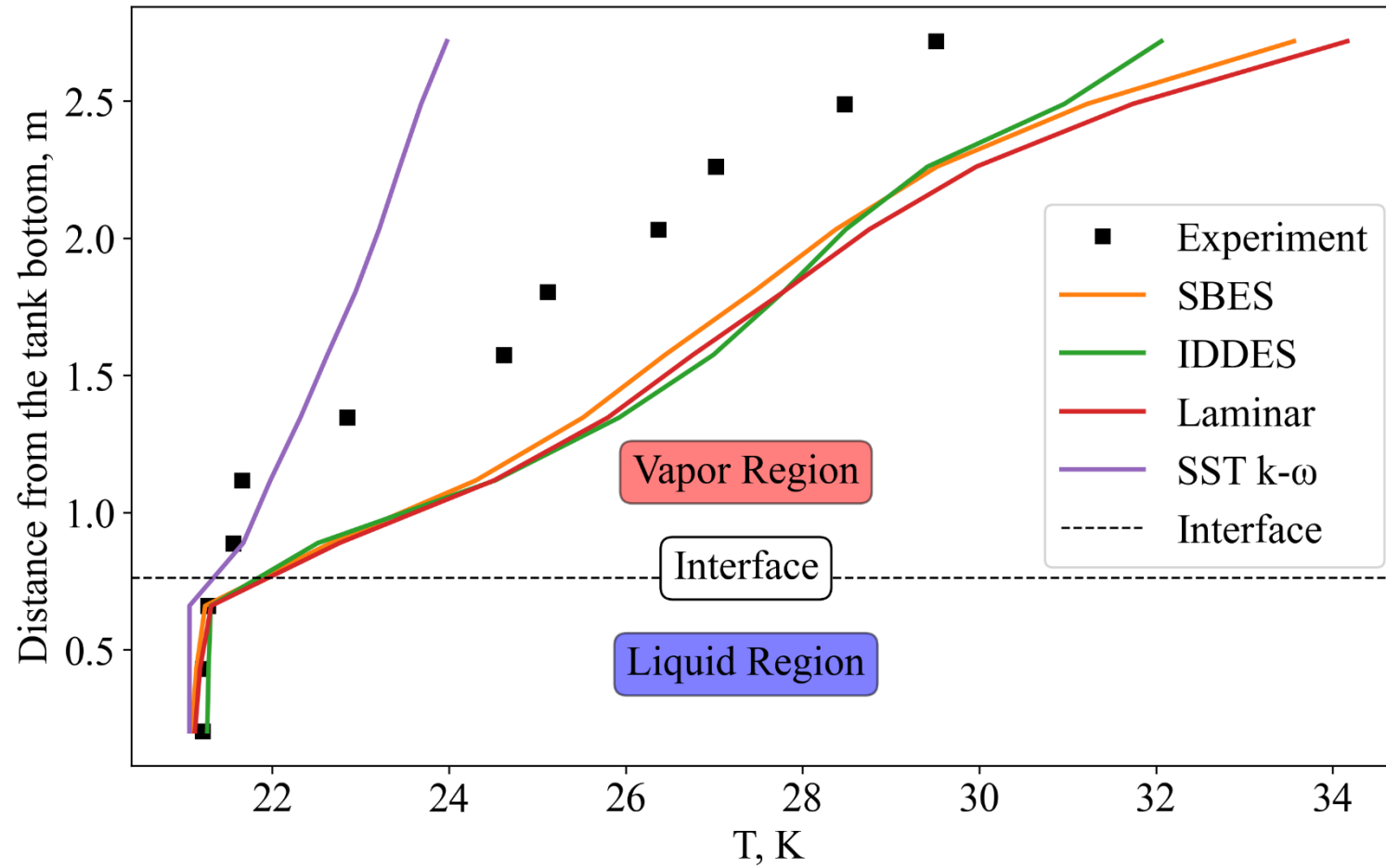
CFD RESULTS: SELF PRESSURIZATION

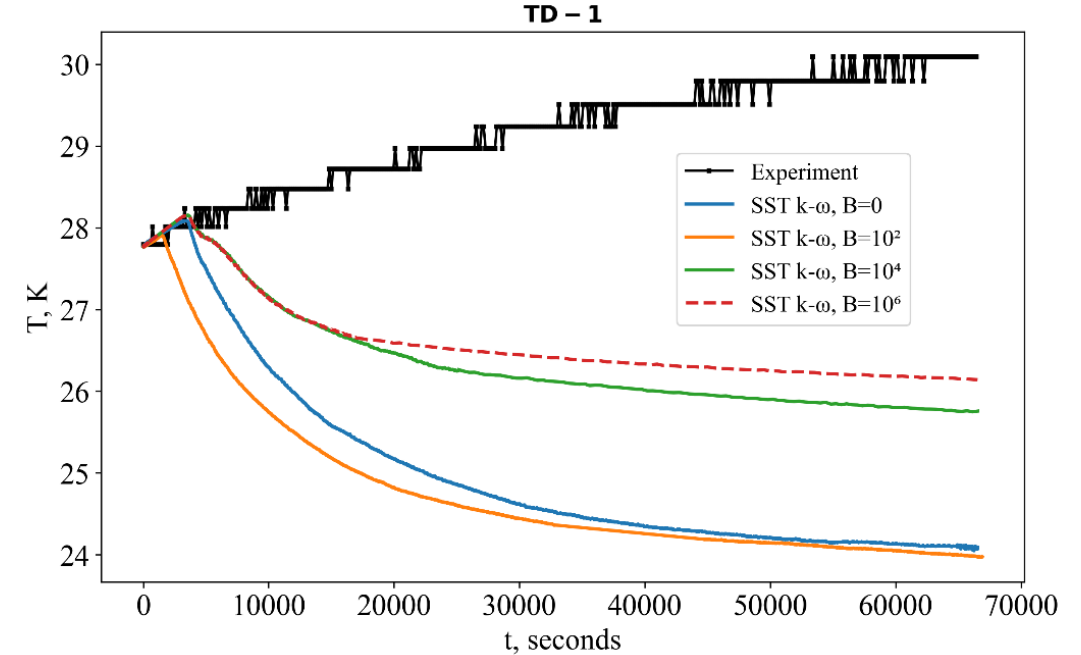
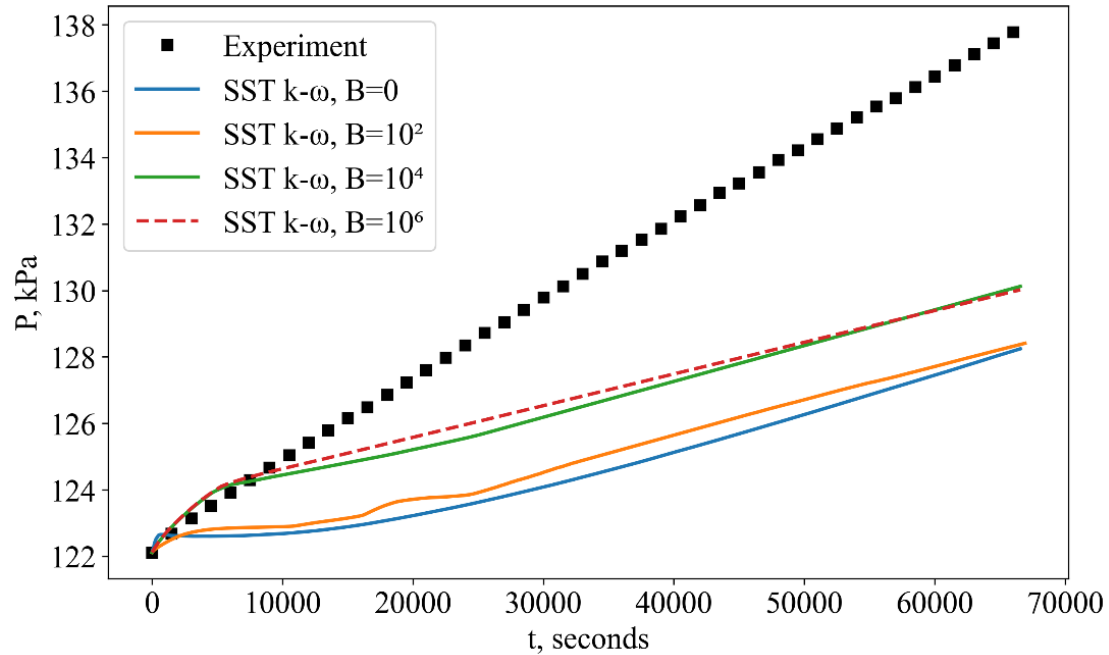




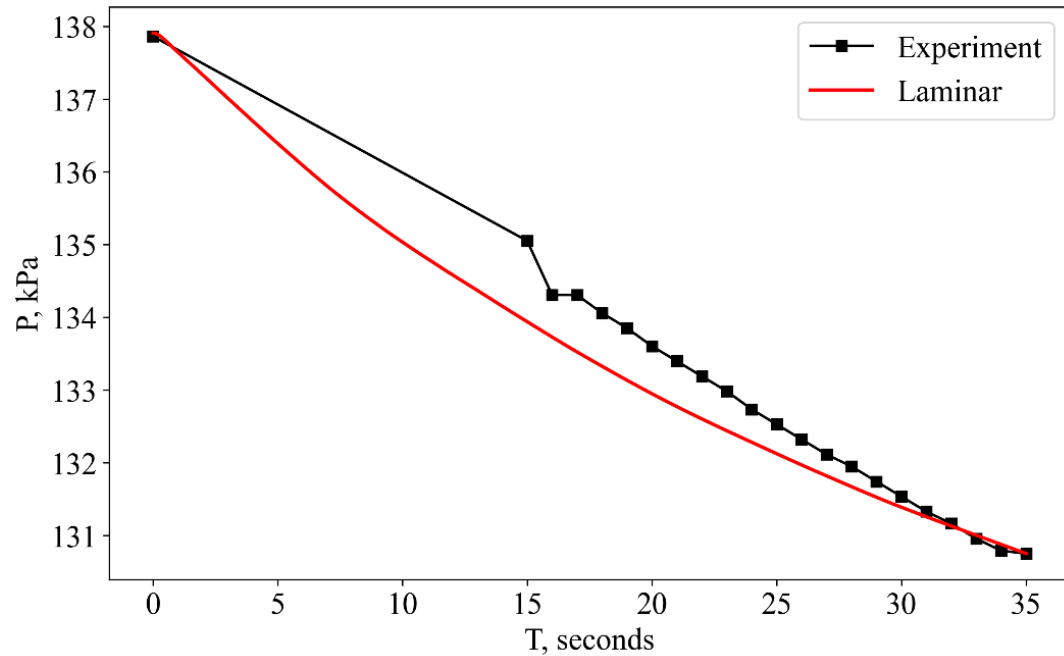
$$\Delta T = T - T_0$$





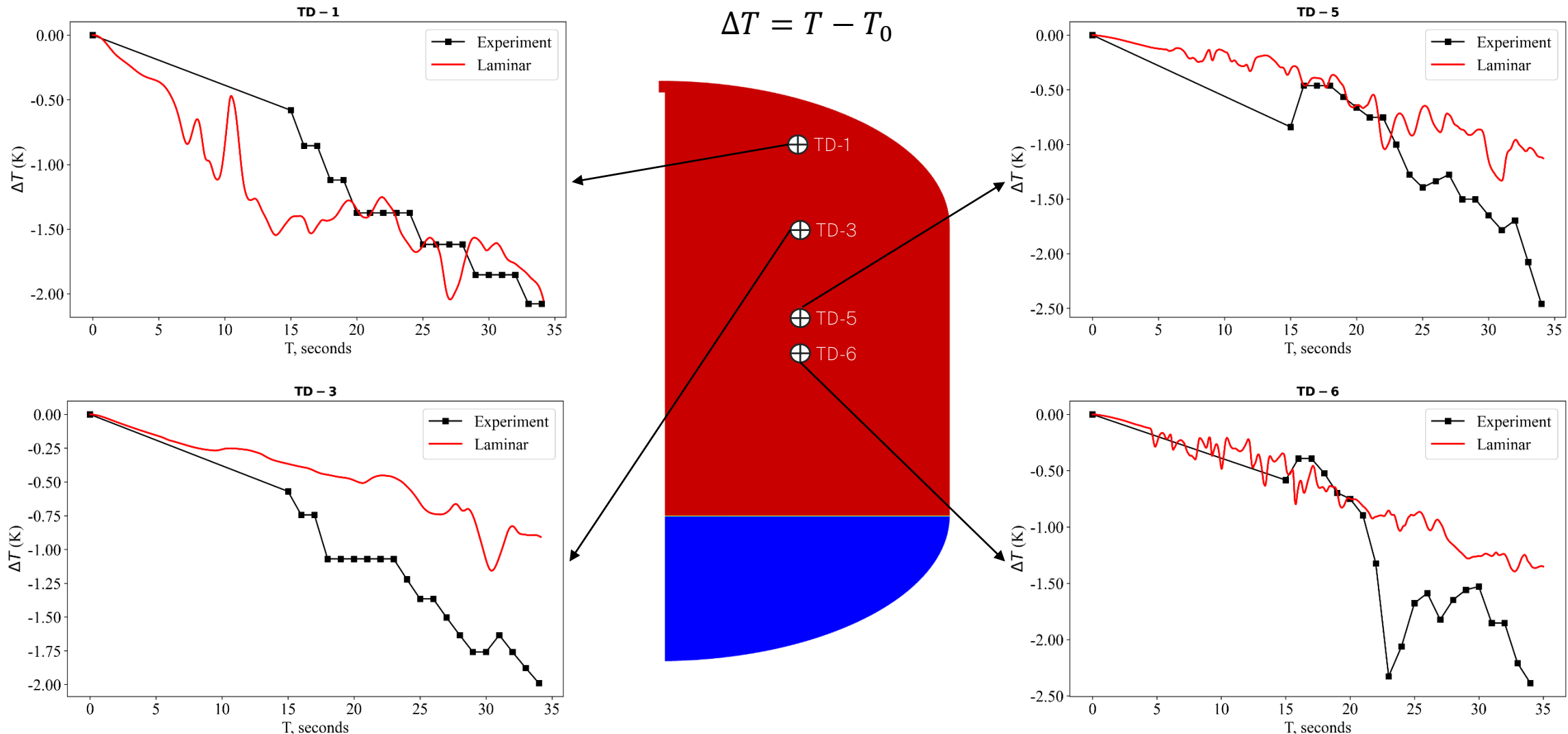


- Increasing damping factor $\rightarrow$ delays the underprediction of the pressure rise and the decrease in temperature, but both phenomena still occur



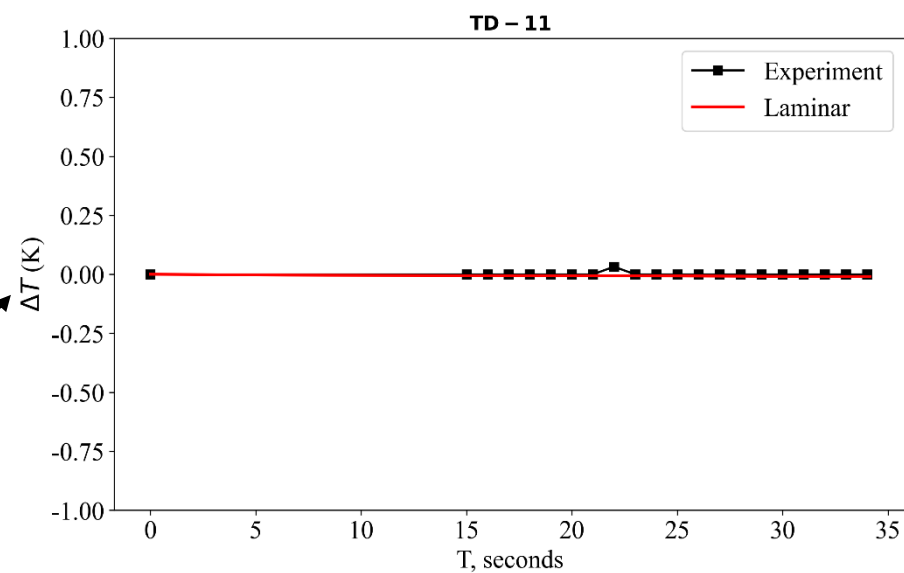
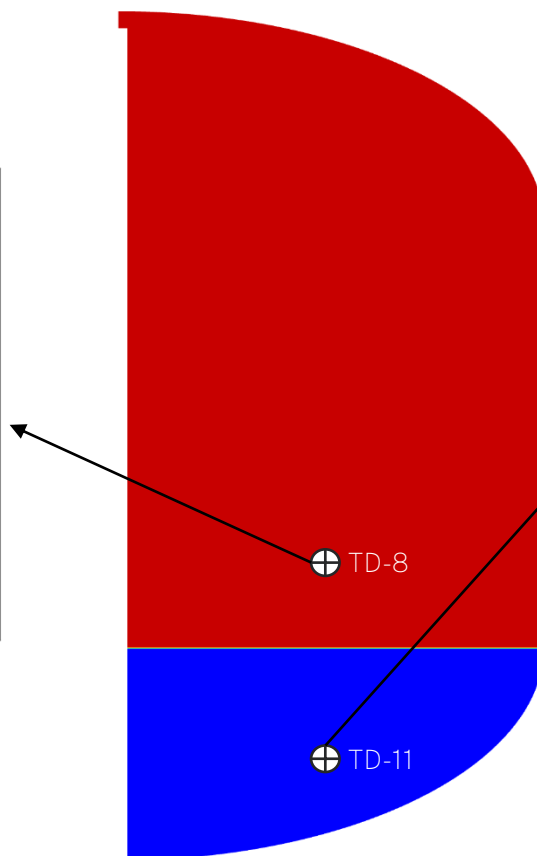
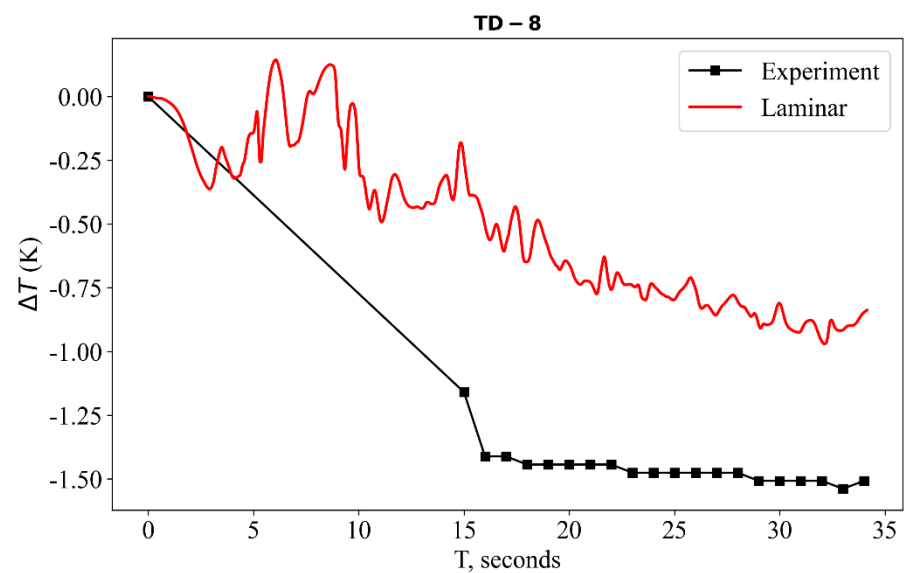
- Strong agreement between CFD and experimental data
- Captures transient behavior and accurate final pressure

CFD RESULTS: SPRAY-BAR MIXING

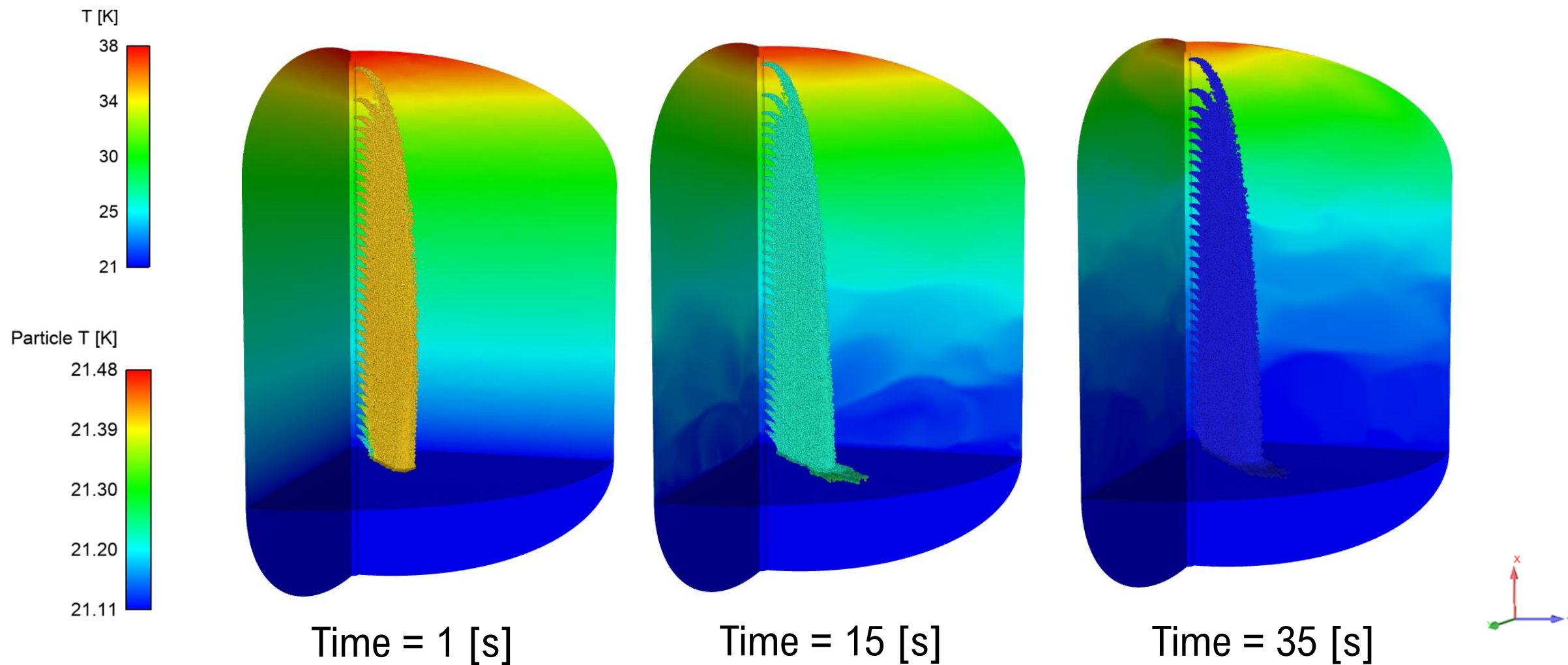


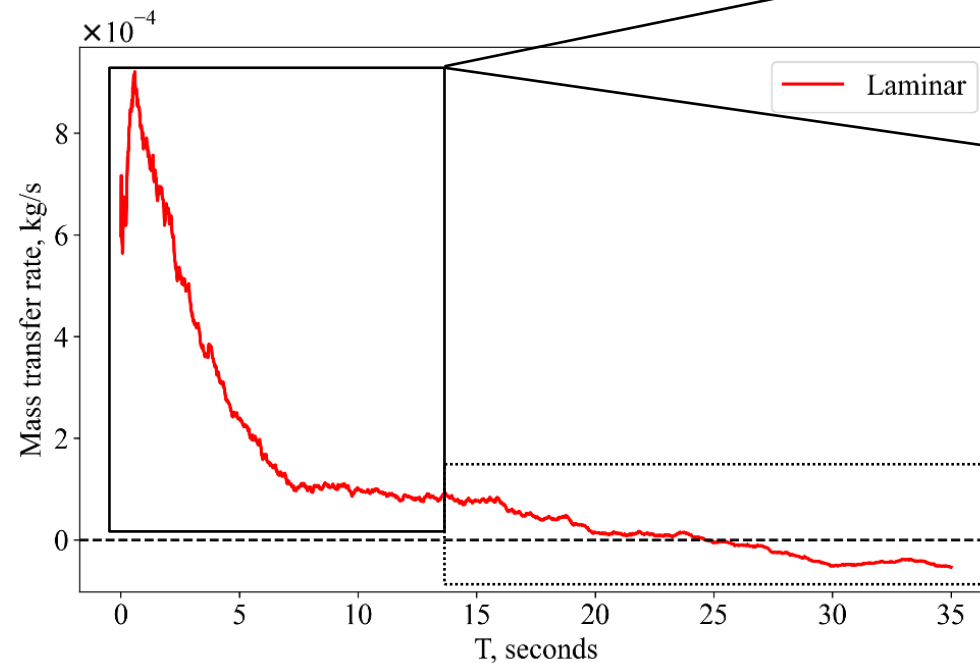
CFD RESULTS: SPRAY-BAR MIXING

$$\Delta T = T - T_0$$



CFD RESULTS: SPRAY-BAR MIXING





- Rapid vapor phase cooling
- Local vapor pressure dropping below saturation pressure of the liquid

- Vapor continues to lose heat to the droplets
- Vapor temperature nearing saturation conditions
- Shift over to condensation

- Validated CFD model accurately predicts pressure and temperature evolution during self-pressurization and spray-bar mixing of the MHTB experiment.
- The IDDES approach provides a good balance of accuracy and computational efficiency for modeling self-pressurization.
- The T-sat model strongly agreed between simulation results and experimental data.
- Future work focuses on multiple spray cycles, varied conditions, and adaptation to microgravity.

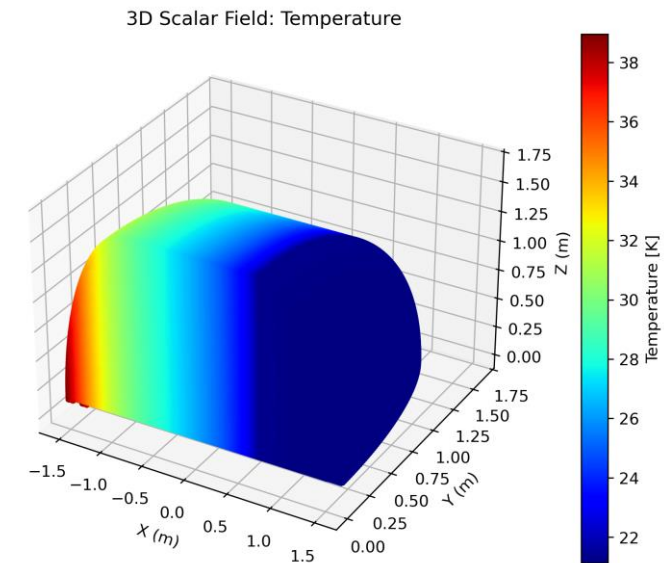
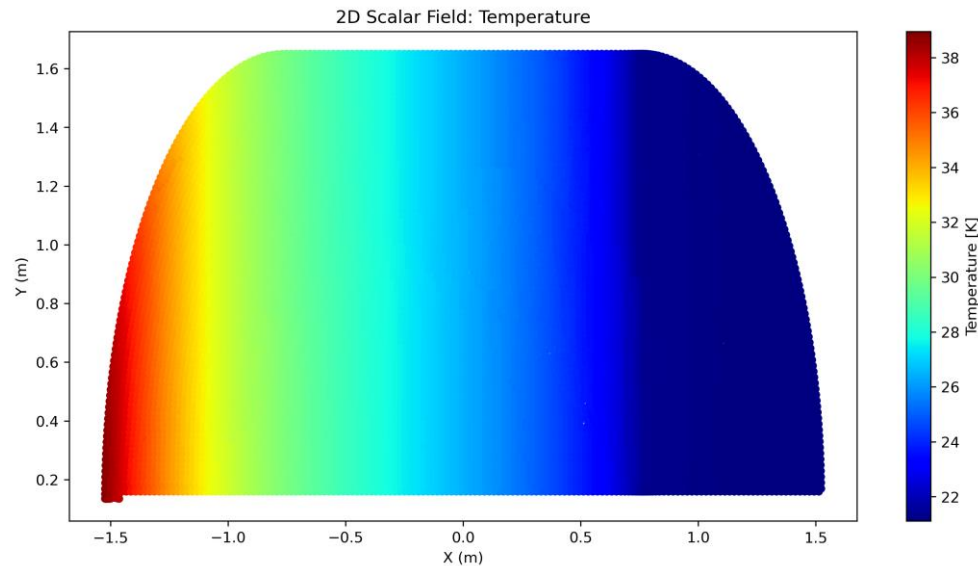
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- 2D Laminar self-pressurization results were transformed into 3D via a Python script and Fluent interpolation files
 - Pressure, VOF, Temperature, and Velocity fields

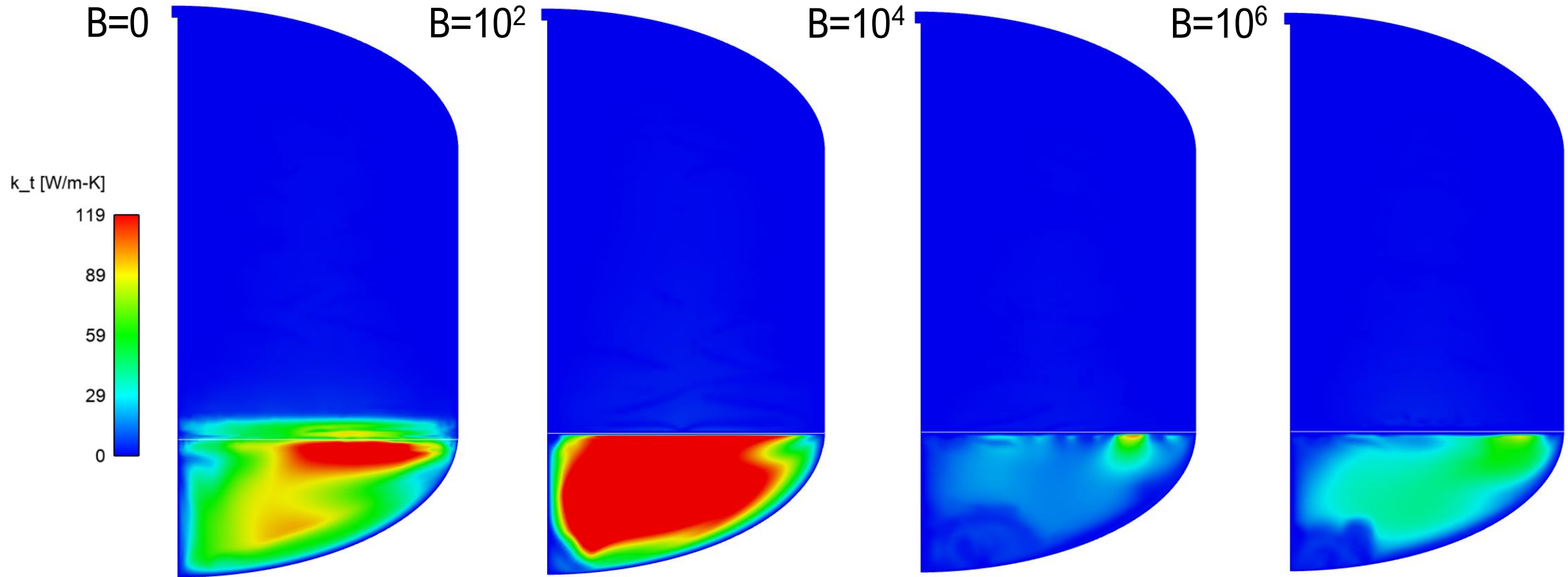


- Effective thermal conductivity (k_t):

$$k_t = \frac{c_p u_t}{Pr_t}$$

- c_p - specific heat
- u_t - turbulent viscosity
- Pr_t - turbulent Prandtl number, by default in Fluent, it is set to 0.85

APPENDIX: EFFECTIVE THERMAL CONDUCTIVITY



Increasing the damping factor, B

Reduces k_t above the interface and in the liquid region