



2025 AIAA SciTech Forum – Orlando, FL



Validation of a Two-Phase CFD Model for Autogenous Pressurization and Expulsion

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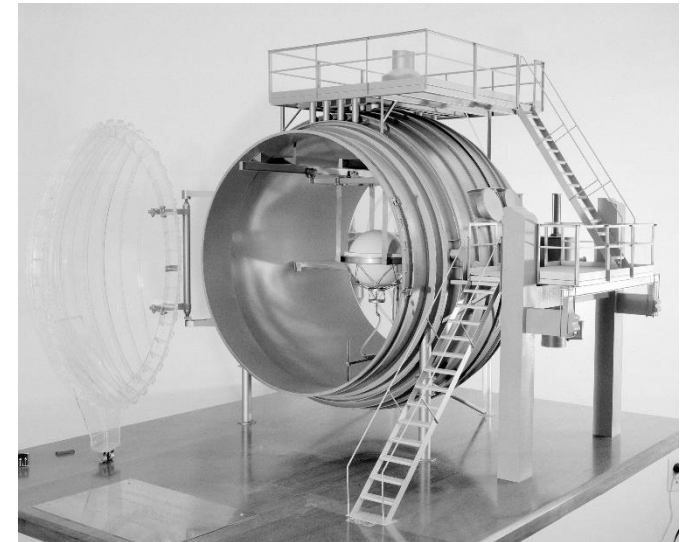
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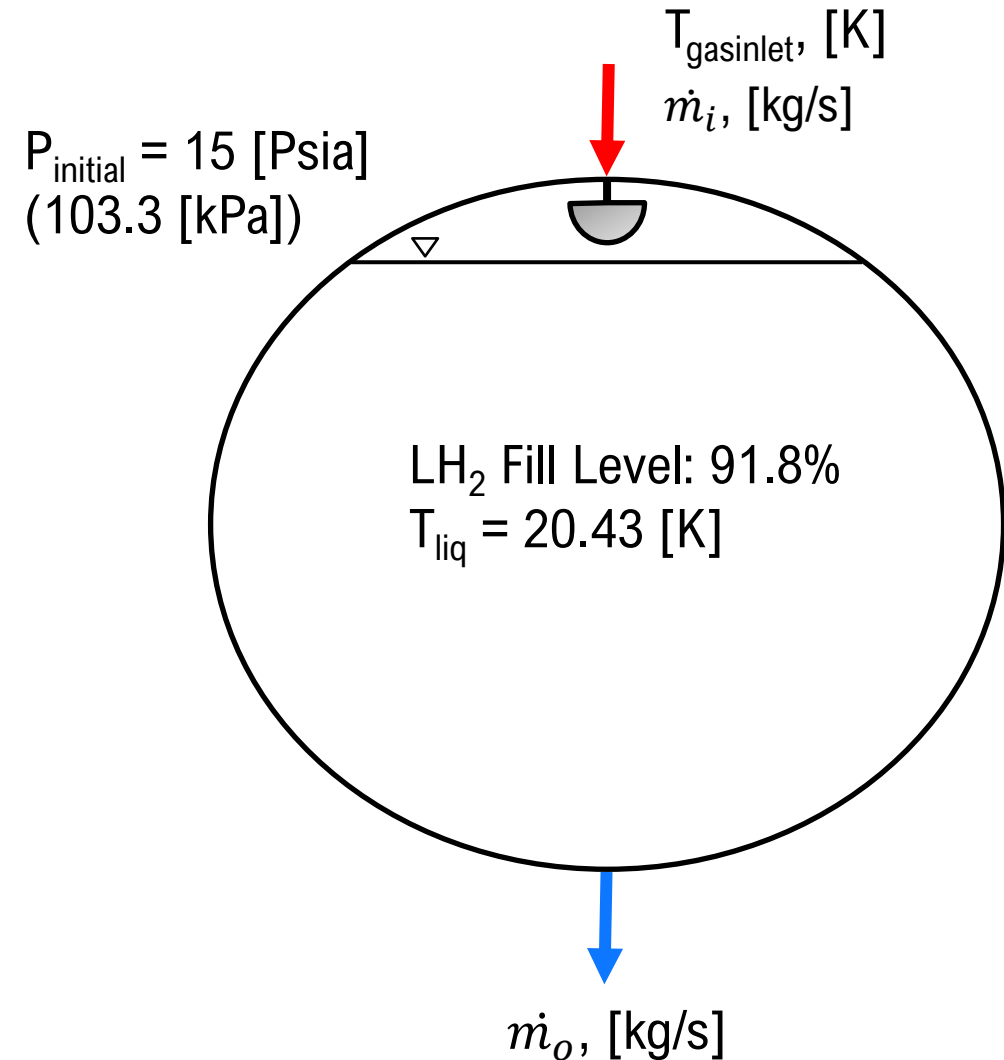
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January 6, 2025

- Cryogenic propellant management is crucial for long-duration NASA missions, especially in microgravity.
- Autogenous pressurization can lead to pressure collapse if vapor condensation is not properly accounted for.
- Ground-based experiments at NASA's K-site facility provide valuable data for validating CFD models.
- Validated CFD models offer a predictive tool to improve propellant management strategies and reduce risks.
- This study focuses on static pressurization and expulsion of liquid hydrogen, enhancing CFD accuracy for future space applications.



- Test conducted at the K-site facility
- Spherical 6061 Aluminum tank
- Tank Diameter: 1.79 [m]
- Tank Volume: 1.75 [m³]
- **Test Procedure:**
 - **Pressurization:**
 - Gaseous H₂ inflow through a diffuser at the top of the tank – **30 [s]**
 - **Hold:**
 - Inflow of gaseous H₂ is reduced, and tank pressure is maintained – **30 [s]**
 - **Expulsion:**
 - Inflow of gaseous H₂ is increased, and liquid is allowed to be expelled at the bottom of the tank – **500 [s]**



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 q^{th} 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):

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

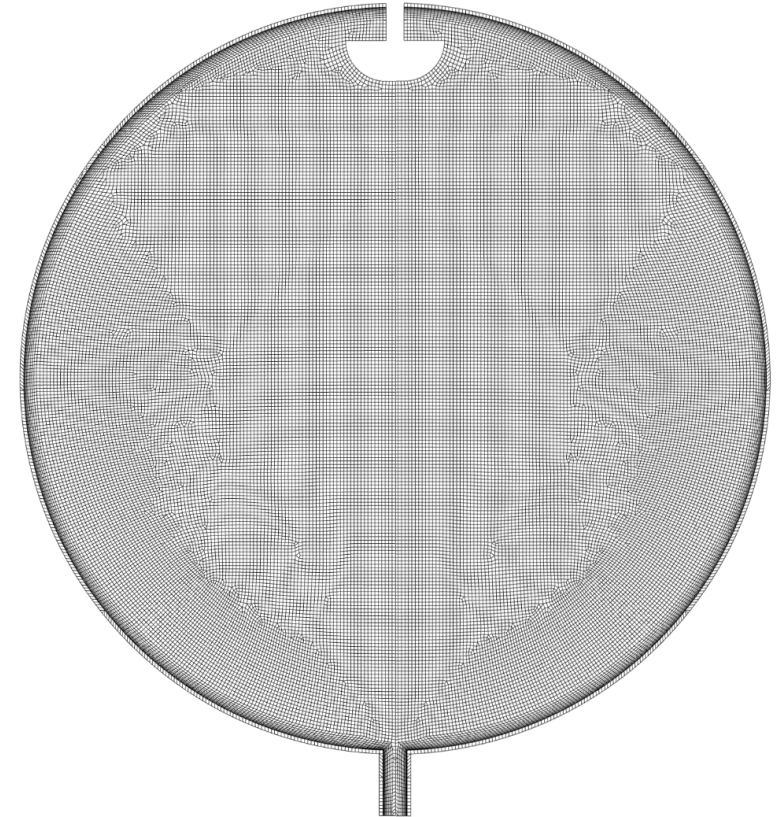
Surface Curvature:

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

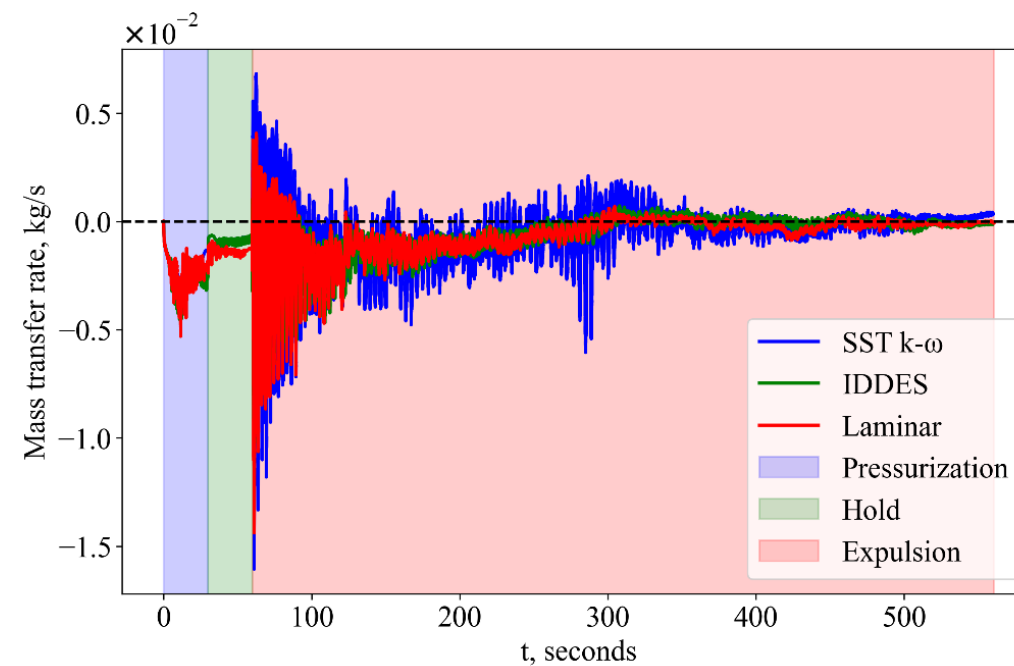
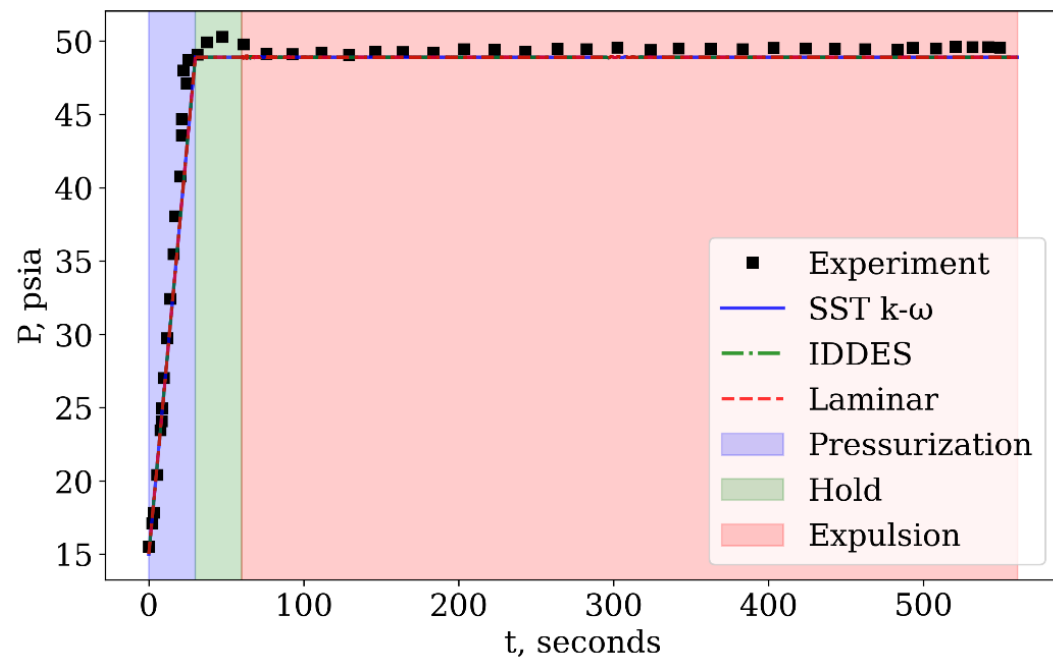
- Simulations performed in ANSYS Fluent version 24.1
- Mass transfer VOF model was integrated into a User defined function (UDF)
- Compressible ideal gas
- Surface tension effects via the Continuum Surface Force method
- Contact angle 0°

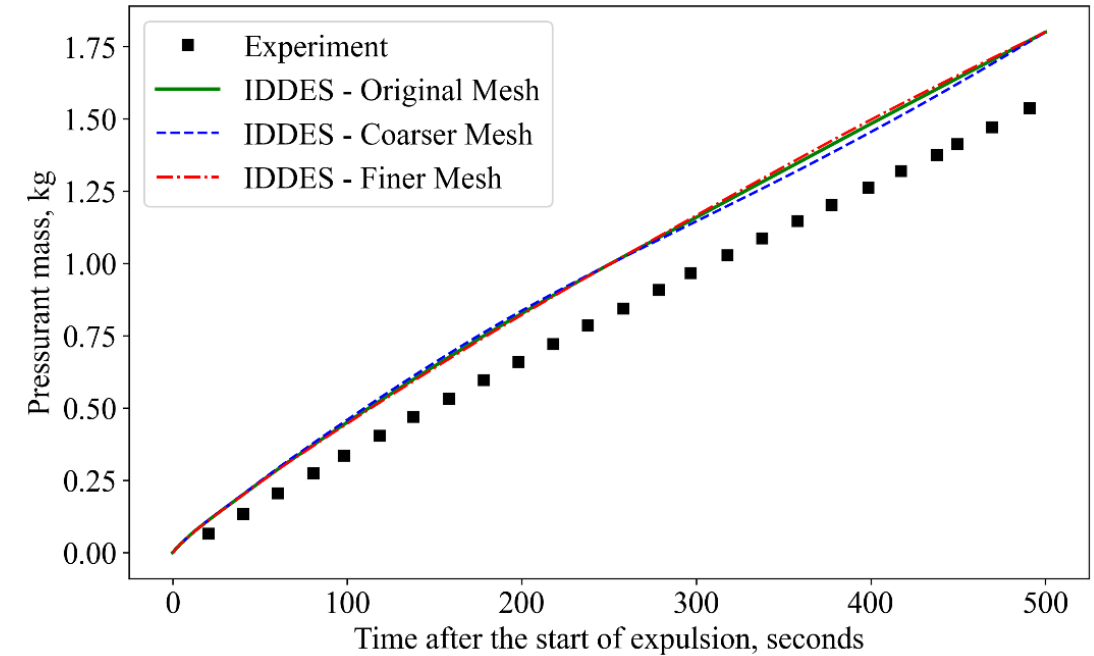
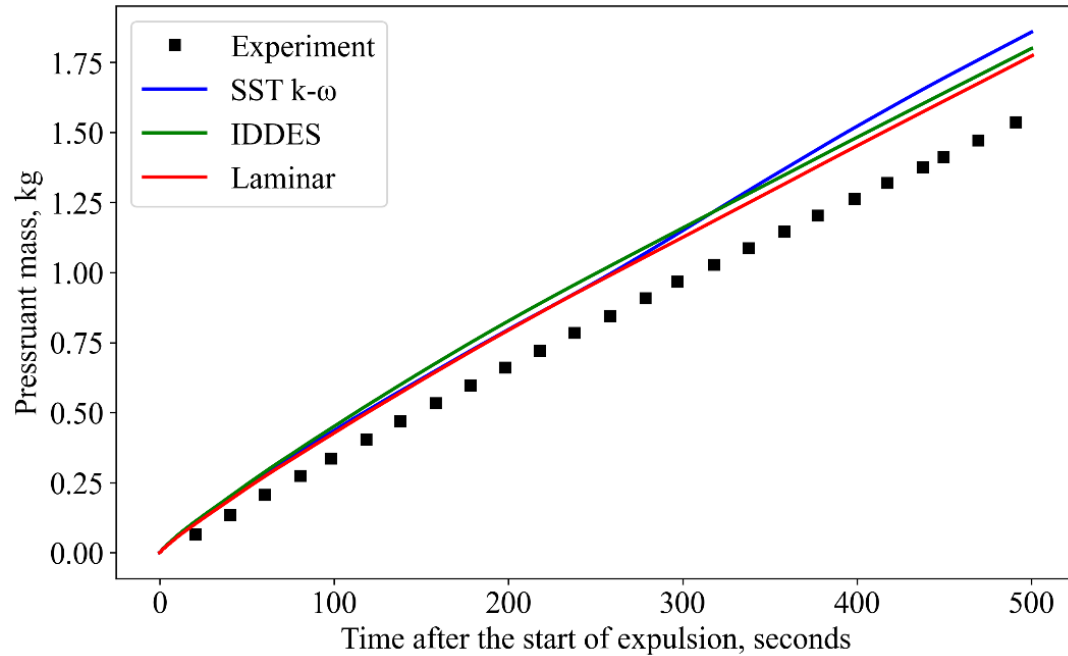
- **Second Order Upwind Scheme** – Energy, Momentum, and Turbulence Equations
- **Bounded Central Difference Method** – Scale-resolving methods
- **PISO Scheme** – Pressure-Velocity coupling
- **Least Squares Cell Based Scheme** – gradient calculations
- **Time step size** – 0.005s

- Tank geometry is modeled
- 2D axisymmetric model is used
- Temperature-dependent properties
- Test procedure is replicated in CFD
- Tank conditions are set to experimental values
- Tank is initially set at the saturation temperature
- Inlet gas temperatures are set to experimental values
- **Computational Mesh:**
 - 5 [mm] average cell size (21,711 cells)



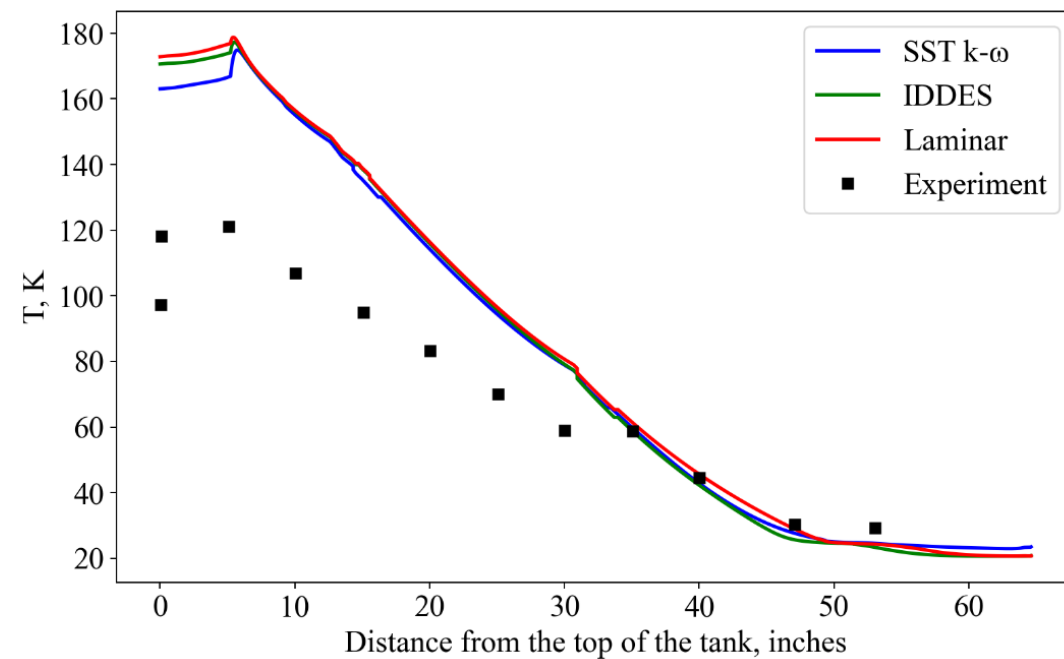
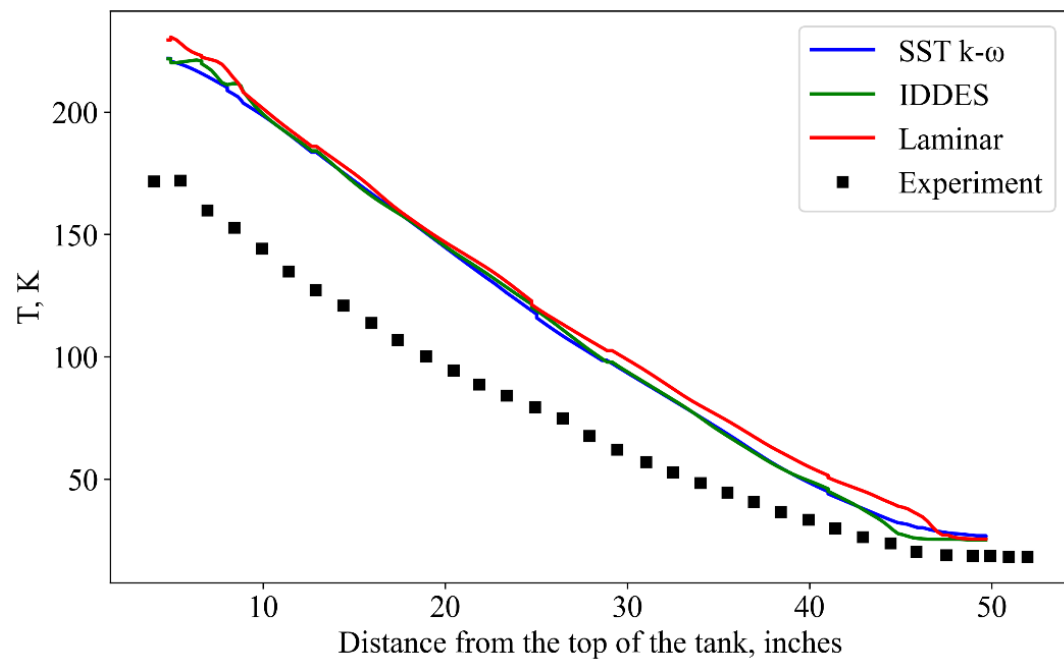
- **Pressurization:**
 - Due to uncertainty in experimental flow rates, a pressure inlet boundary condition was implemented to match the experiment pressure rise
- **Hold:**
 - Pressure inlet boundary condition
- **Expulsion:**
 - Proportional controller implemented via UDF to maintain tank pressure
- **Turbulence Models:**
 - Laminar
 - SST k- ω
 - Improved Delayed Detached Eddy Simulation (IDDES)

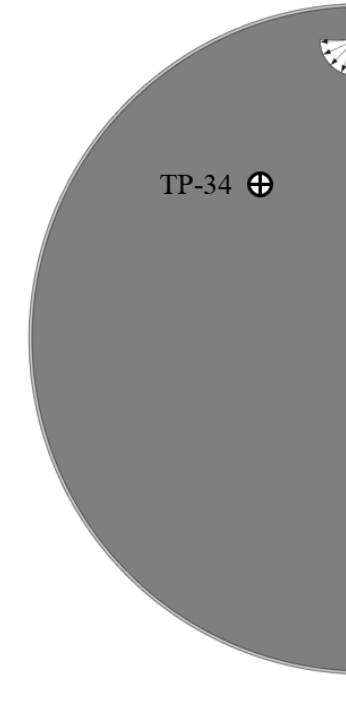
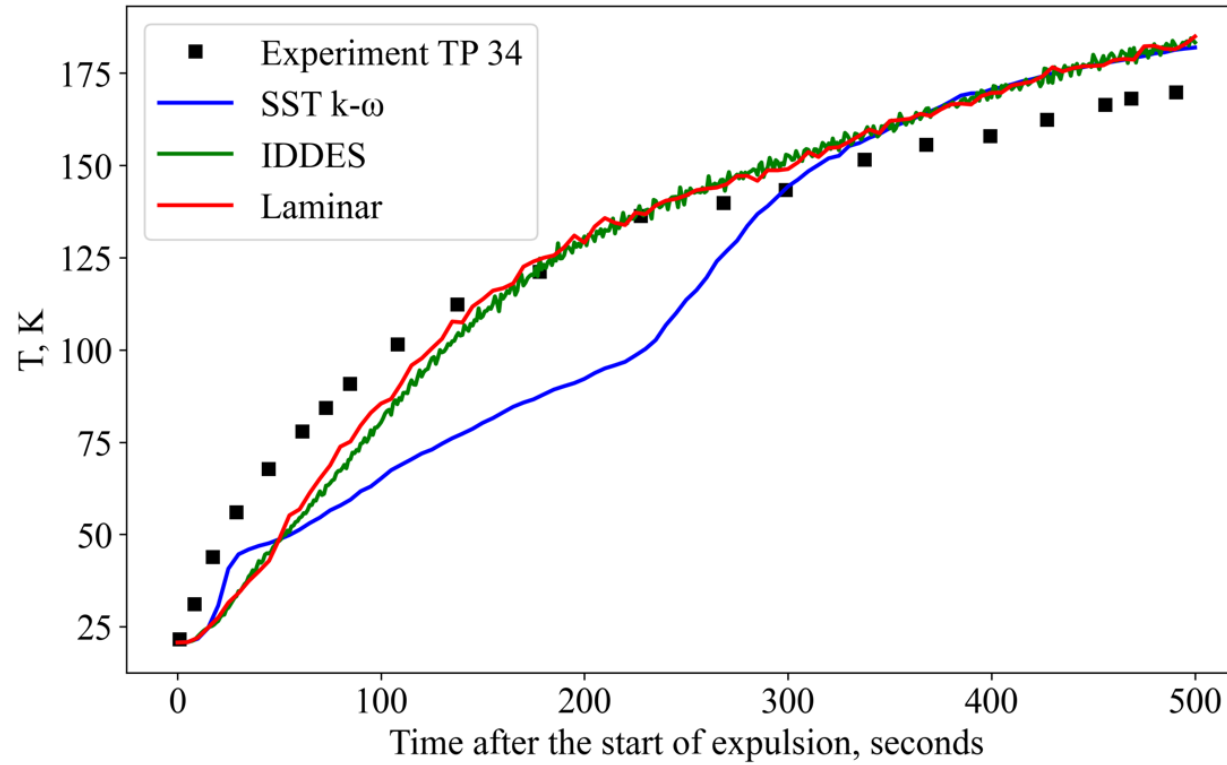




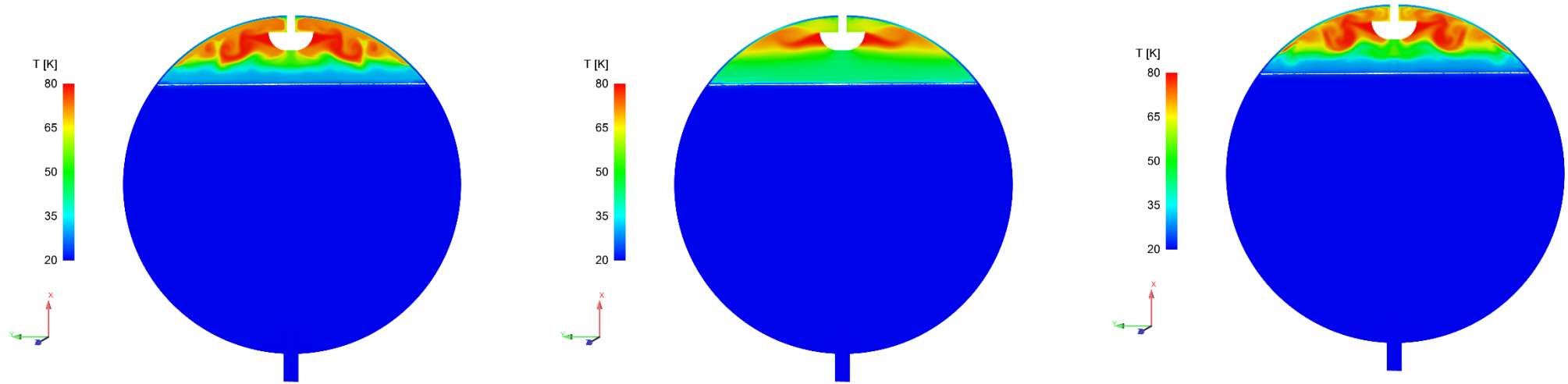
Coarse Mesh: average cell size **10 [mm]** (11,411 cells)
Original Mesh: average cell size **5 [mm]** (21,711 cells)
Finer Mesh: average cell size **2.5 [mm]** (80,330 cells)

Time = 493 [s] into the expulsion

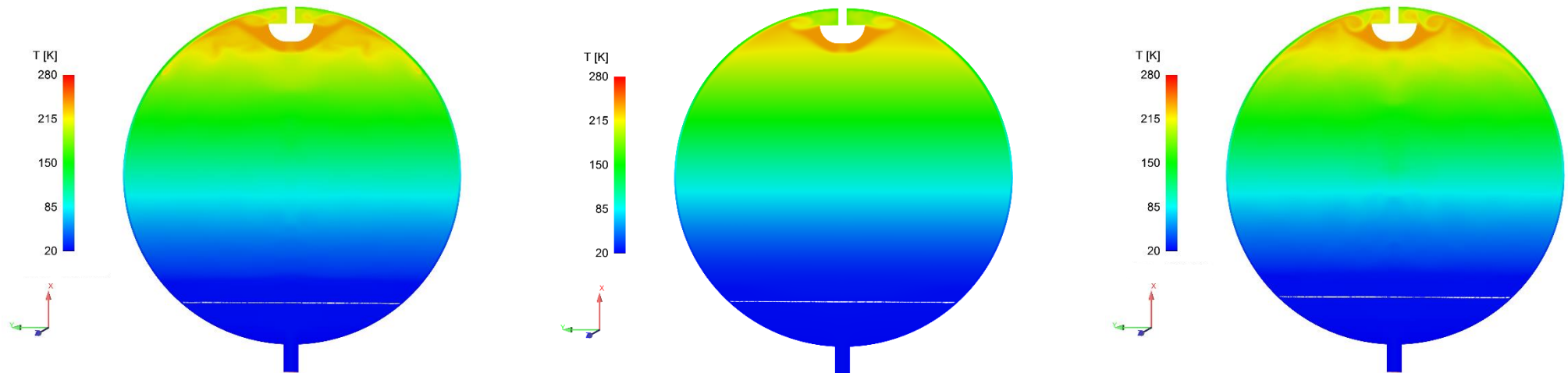




Beginning
of Expulsion
0 [s]



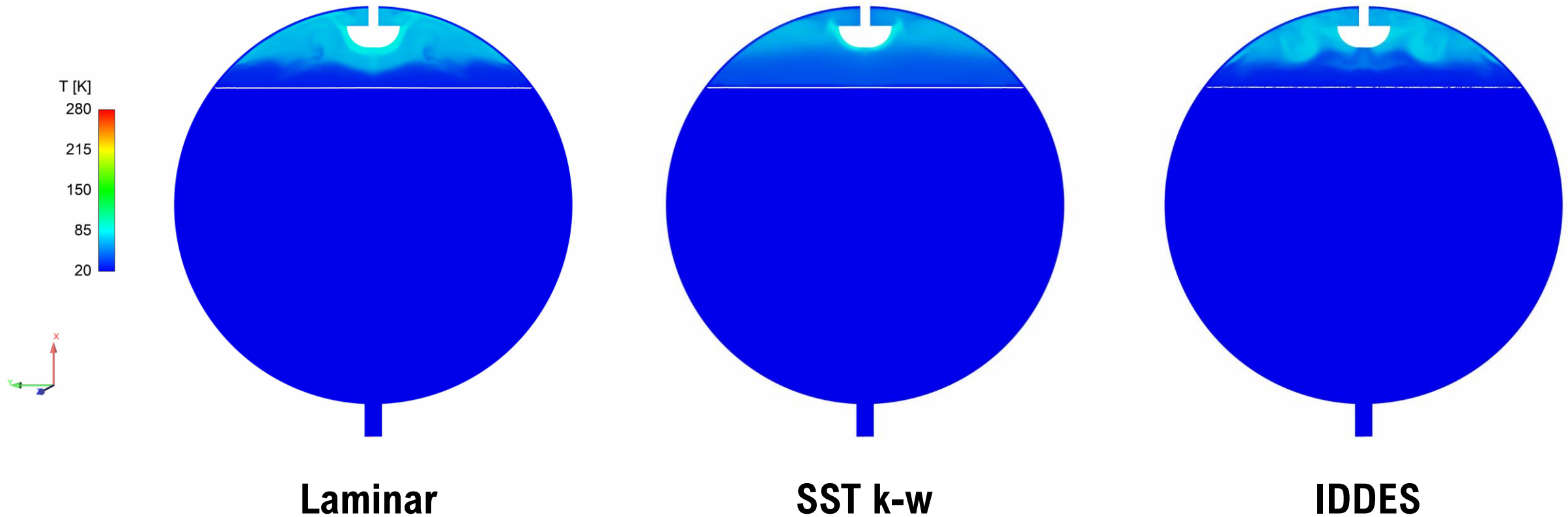
End
of Expulsion
500 [s]



Laminar

SST k-w

IDDES



- Developed and validated a CFD model for autogenous liquid hydrogen tank pressurization and expulsion using K-site experimental data.
- Achieved good agreement with experimental pressure trends and pressurant mass usage.
- Temperature predictions captured trends but overestimated actual values, which can be attributed to assumptions made during pressurization.
- Comparing laminar, SST k-w, and IDDES models showed that all could predict overall trends, with laminar and IDDES better-matching temperature evolution.
- Future work includes testing other turbulence models (LES), adjusting boundary conditions, and reducing data gaps for improved accuracy.

The authors would like to thank the Modeling Portfolio Project within the STMD CFM Project Office for funding this work.



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P-Controller:

$$\dot{m}_{\text{in}} = \dot{m}_{\text{in, previous}} + k (P_{\text{set}} - P_{\text{avg}}) \quad K = 0.005$$