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CFD Modeling of Tank Pressurization and Axial Jet Mixing Experiments with and without Non-Condensable Gas in the Ullage

O. Kartuzova, M. Kassemi

*National Center for Space Exploration Research (NCSER)
at Case Western Reserve University and NASA Glenn Research Center
Cleveland, OH, USA*

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Test description

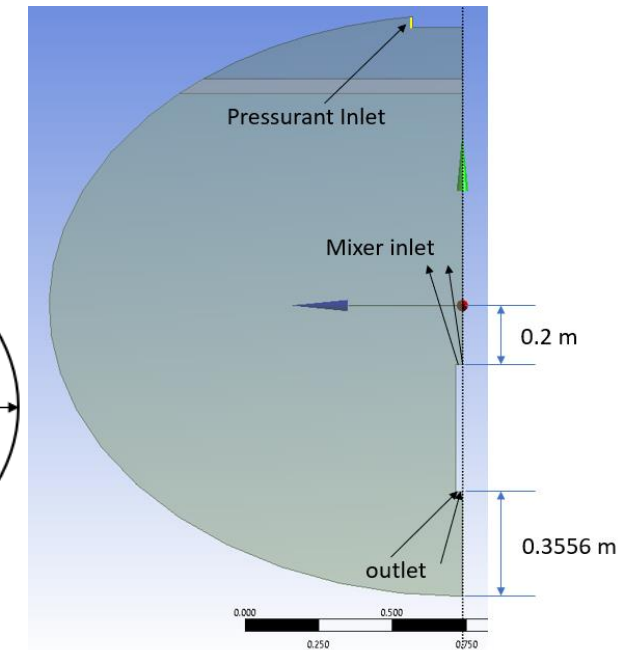
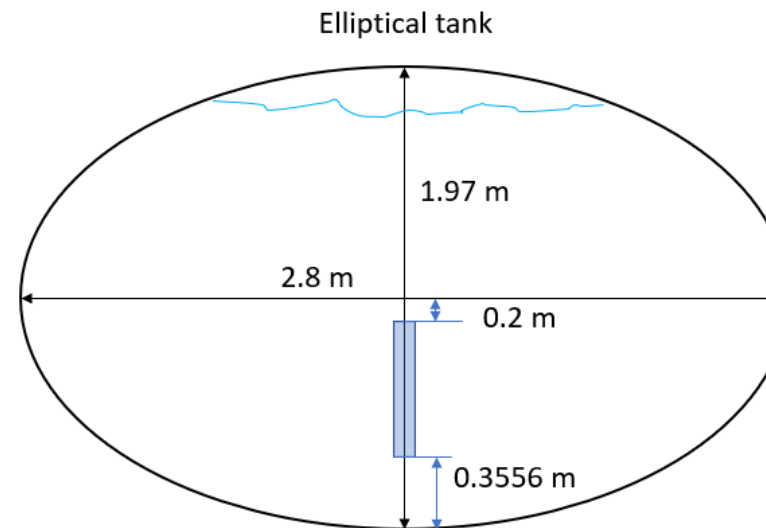
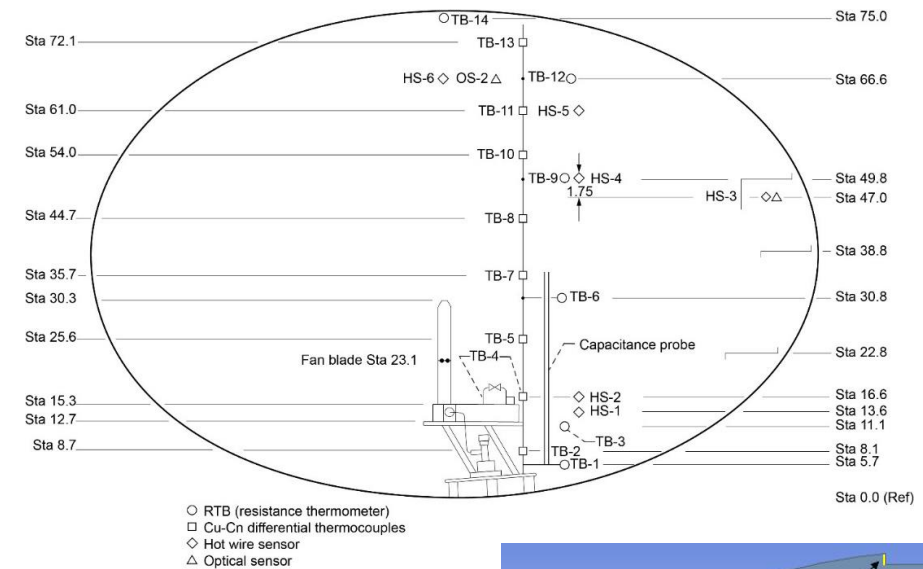


Experiment

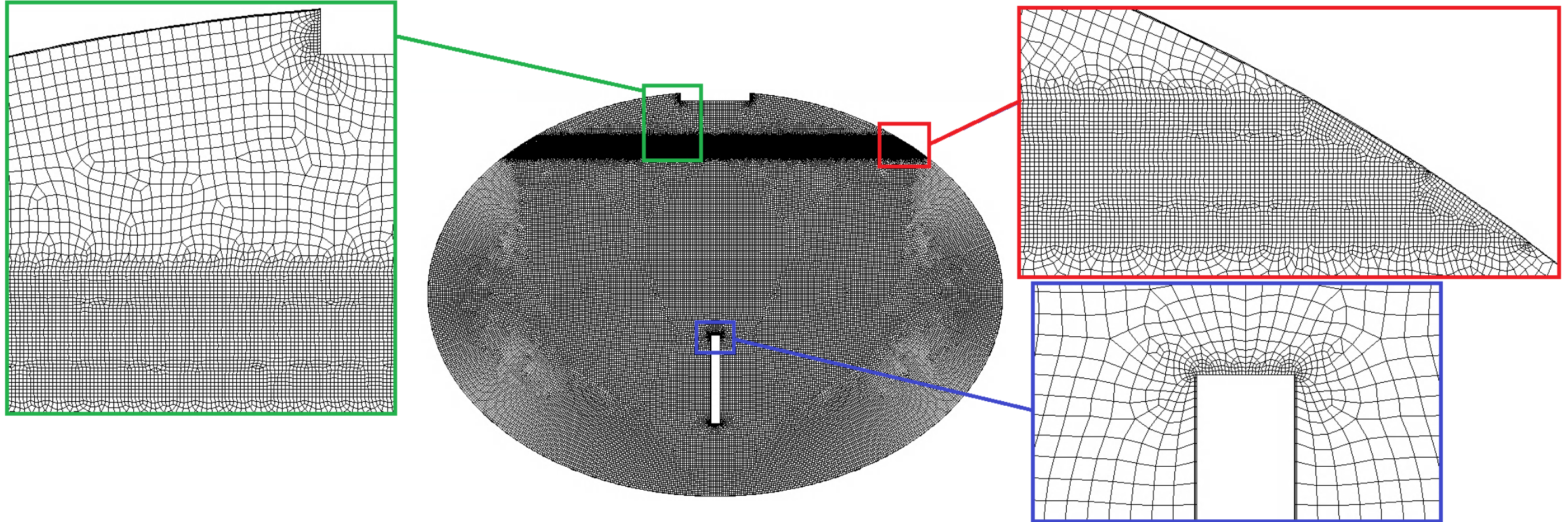
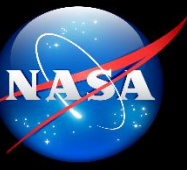
- A bottom mount 110-inch diameter tank;
- Gaseous H₂ (case 9) or He (case 30) is added at the top of the tank during pressurization.
- Pressurization is followed by jet mixing.

CFD

- 2D axisymmetric geometry with tank wall not included
- VOF Model
- 95% fill level considered
- GH₂ or GHe injected at the Pressurant Inlet
- Pressurant mass flow rate of 1.89 g/sec and T=77K applied uniformly at the surface of the injector as B.C.
- During mixing gas injection turned off. Liquid mass flow rate = 150 L/m.



Computational mesh



2D axisymmetric - 35,070 cells

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
 P_v - in the cases with non-condensable gas is defined as a partial pressure of hydrogen vapor.
 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 $kg/(m^2 \cdot sec)$.

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

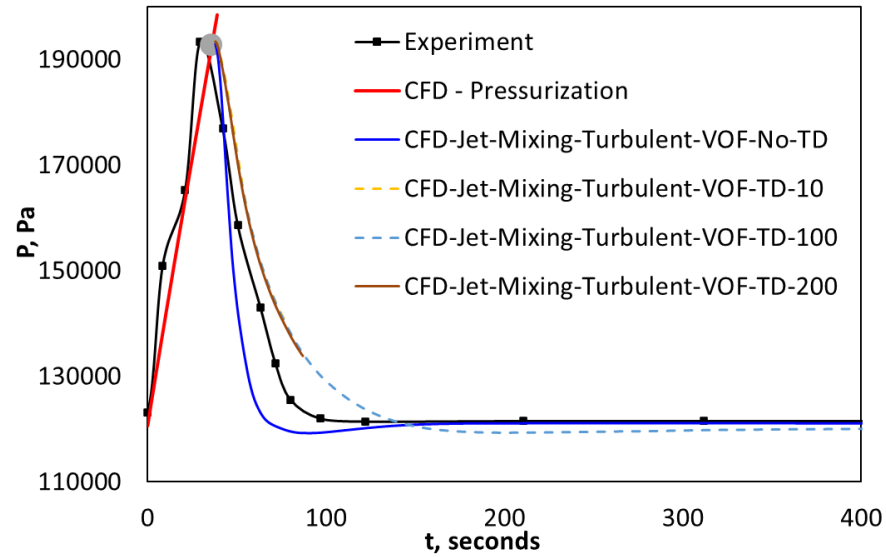
Computational Model: Numerical Methods



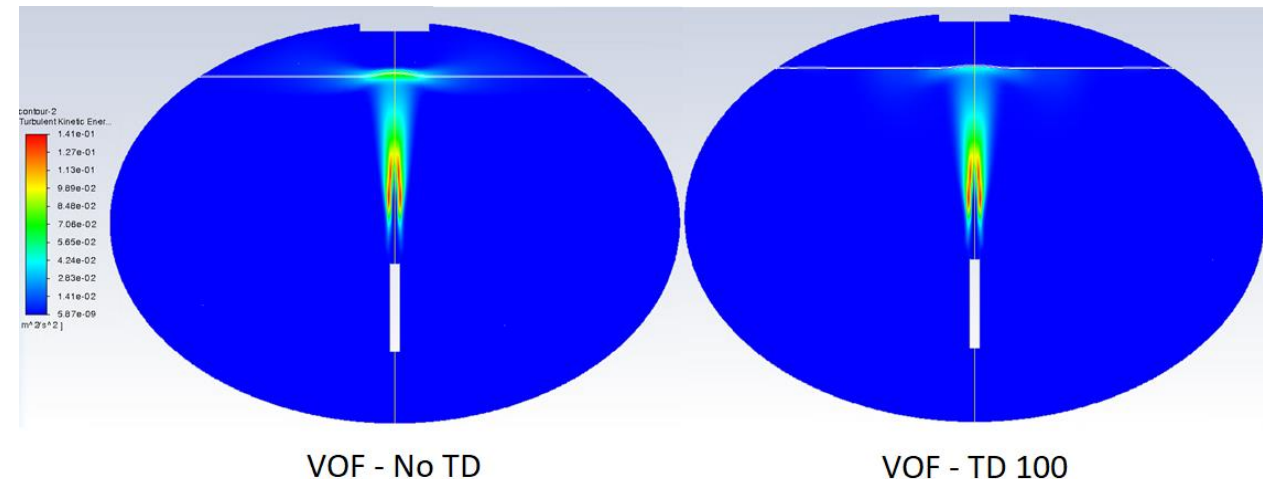
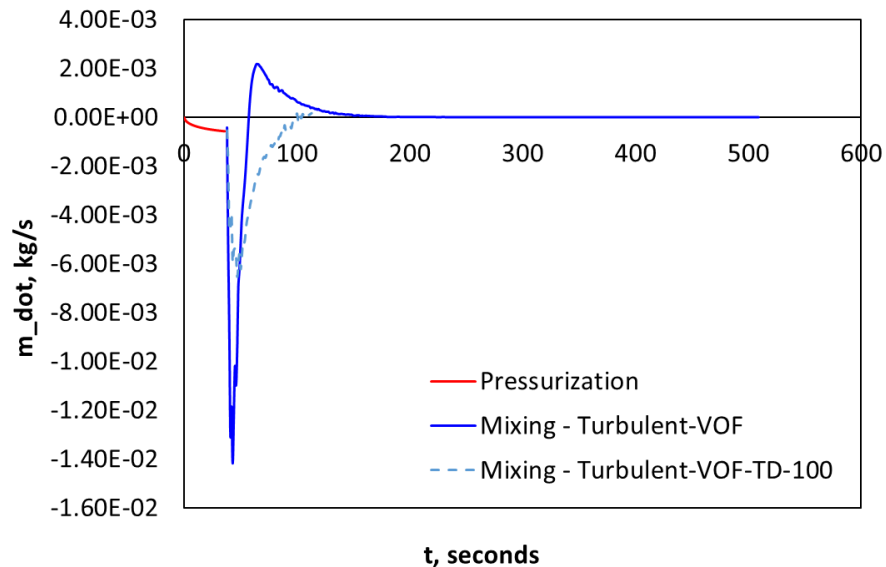
- Simulations performed using ANSYS Fluent version 23.1
- **2D axisymmetric** geometry was modeled
- Compressible ideal gas
- Surface tension effects via Continuum Surface Force method of Brackbill et al.
- Contact angle 0°

- 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)
- PRESTO! 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
- Second Order Implicit temporal discretization was used with implicit Compressive VOF model with $\Delta t = 0.001$ s

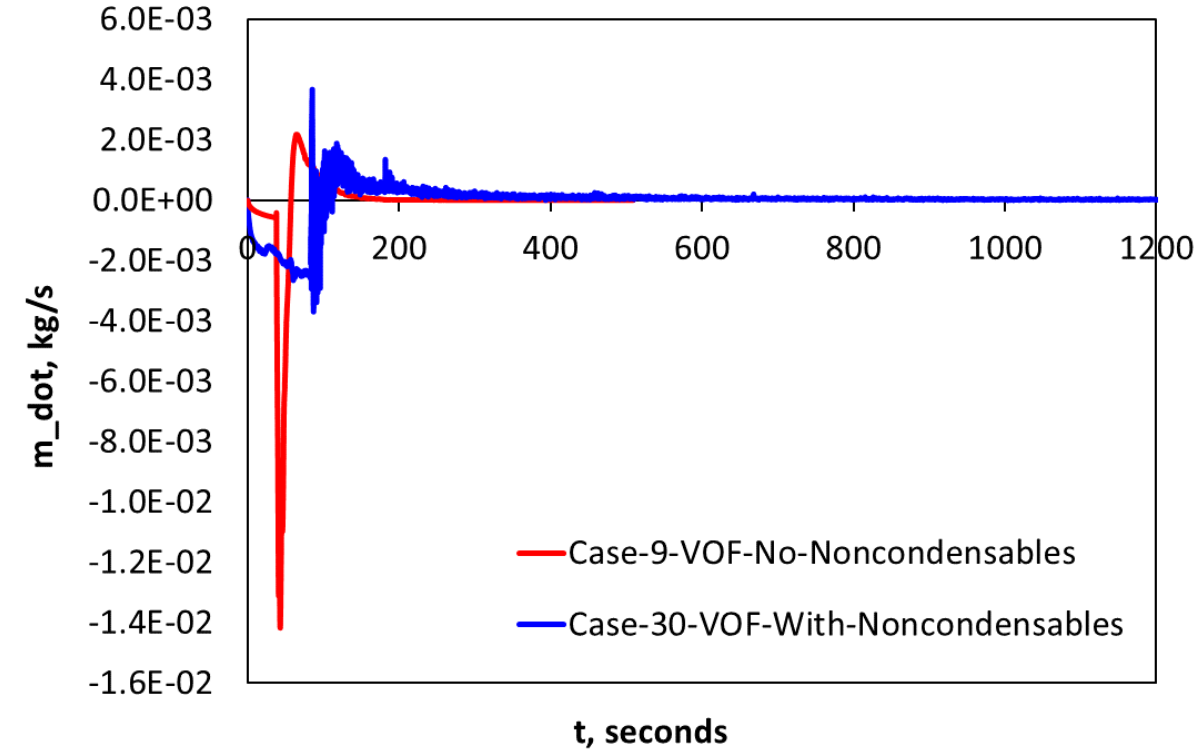
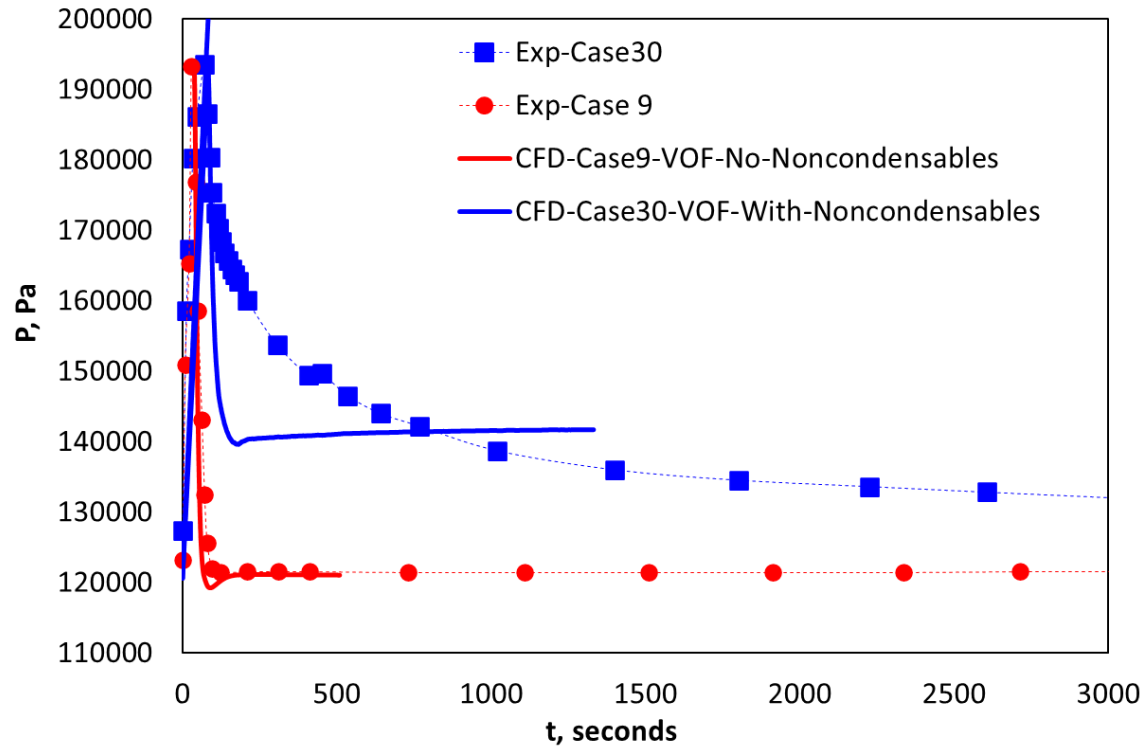
CFD Results – GH2 Pressurization and mixing



- Predicted final tank pressure matches experiment
- Studied effects of turbulence damping (TD) at the interface
- Cases with damping predict less condensation and higher tank pressures
- Value of TD has no effect
- Cases with TD limit higher levels of turbulence kinetic energy to the liquid side



CFD Results – GHe Pressurization and mixing



- Tank pressure decreases slower in the case with GHe pressurization compared to the cases with GH2 pressurization in both experiment and CFD
- CFD predicts significantly less condensation in the case with GHe pressurization, which is Noncondensable in this case
- While predicted tank pressures matches experimental ones well in the case with GH2 pressurization, tank pressures are under-predicted in the case with GHe pressurization in the beginning of mixing

Conclusions:



- A computational model of tank pressurization followed by jet mixing with and without non-condensable gas has been developed and results were compared with experimental data
- For the like-gas pressurization (experimental case 9) and the following jet mixing the turbulent VOF model's predictions matched the measured pressures in the tank reasonably well
- In the case with the non-condensable gas pressurization (experimental case 30), turbulent VOF model over-predicted the pressure drop compared to the measurements.
- Current VOF model does not include a rigorous balance of species at the interface, nor does it follow Henry's Law in determining the species concentrations at the vapor and liquid side of the interface. It also does not capture the dissolution of helium in liquid hydrogen. This model must be improved to remove these shortcomings so that it can provide more accurate predictions of the noncondensable gas effects.

Acknowledgements



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