Autogenous Pressurization of a Cryogenic Tank using Computational Fluid Dynamics

Bruce Ciccotosto, Daniel Hauser
NASA Glenn Research Center

Introduction

- Autogenous pressurization: Small amount of liquid is removed, vaporized, pressure increases from change in density
  - reduce boiloff, prevents cavitation in turbopumps, propellant transfers.

- Space is hard. Cryogenic propellant testing is too
  - Expensive, dangerous, complex, unintuitive
  - There is a need for validated simulation tools to develop this technology

- Presenting a multiphase CFD model in STAR-CCM+ to predict pressure rise and temperature stratification of cryogenic autogenous pressurization
  - Quantify difference to experimental data with transient error metrics

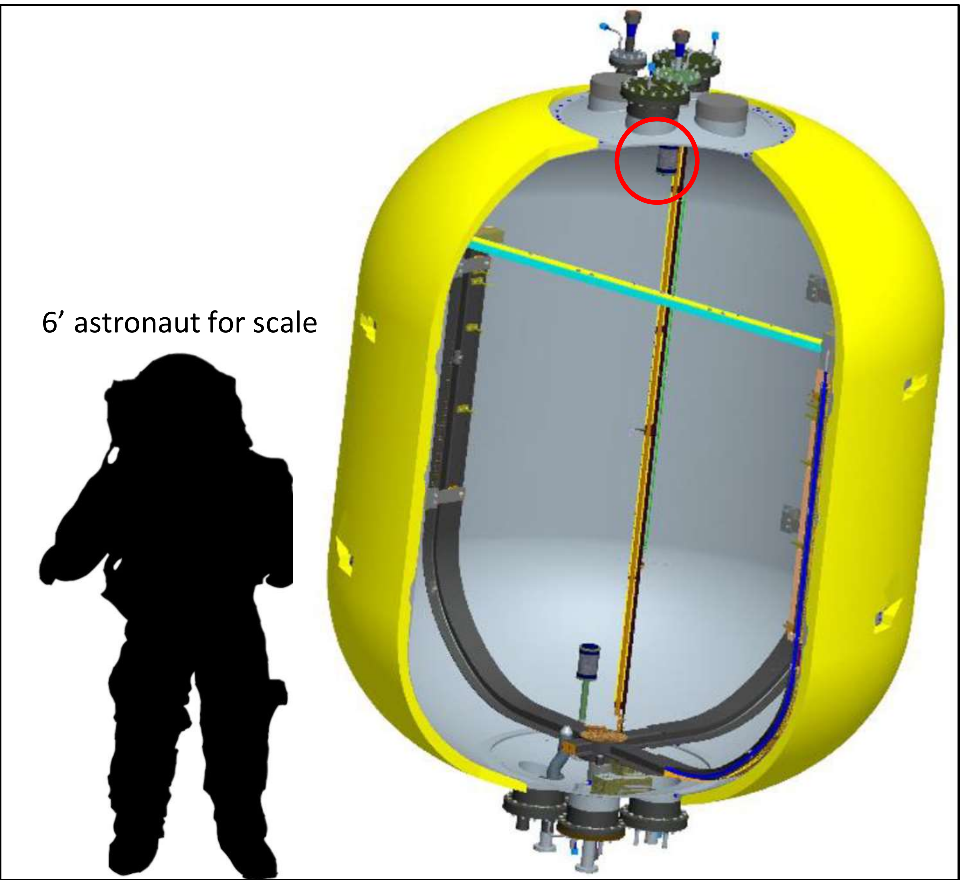
Experimental Background and CFD setup

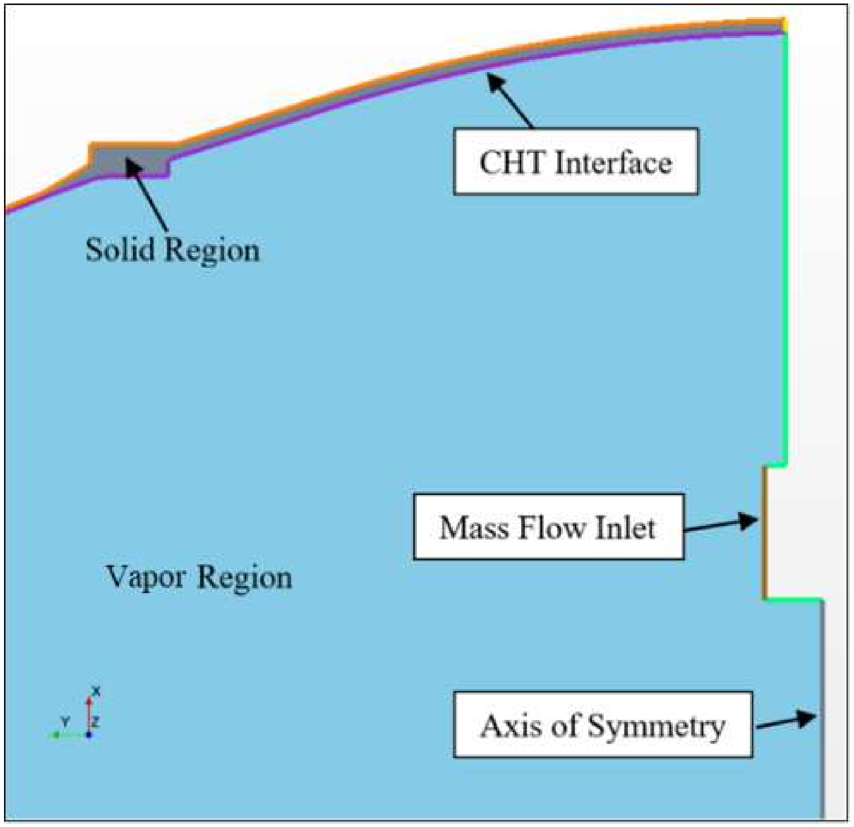
Engineering Development Unit (EDU) test article

- 4520 liters, max internal radius of 850 mm
- walls nominal 2.5 cm thick, aluminum 2219
- 60 layers of insulation, vacuum chamber
- Ullage diffuser, autogenous GN2/LN2 test
- 25% liquid fill by volume

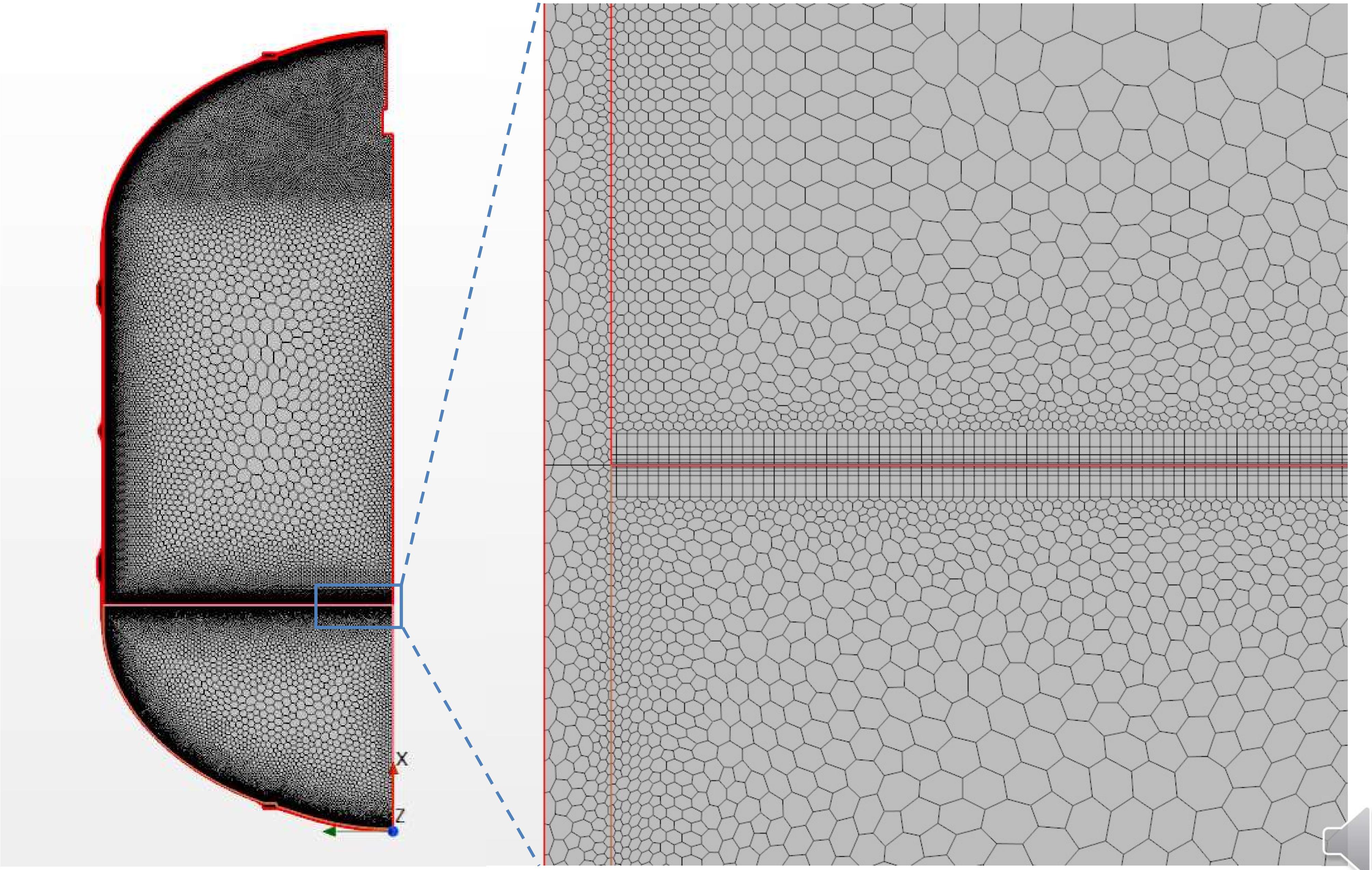
Key assumptions

- Terrestrial gravity, quiescent, flat stationary interface
- Simplify internal geometry, axisymmetric
- Diffuser flow is uniform
- Adiabatic outer walls
- Constant material properties
- Ra = 2E6, flow is laminar





Computational Grid



Multiphase CFD methods

Volume-of-Fluid

- one set of gov. eqns.
- volume fraction continuity
  - additional closure relations as needed plus phase interactions
  - Mass transfer via Schrage equation[1]
    - Successful in previous multiphase CFD on cryogens[2]

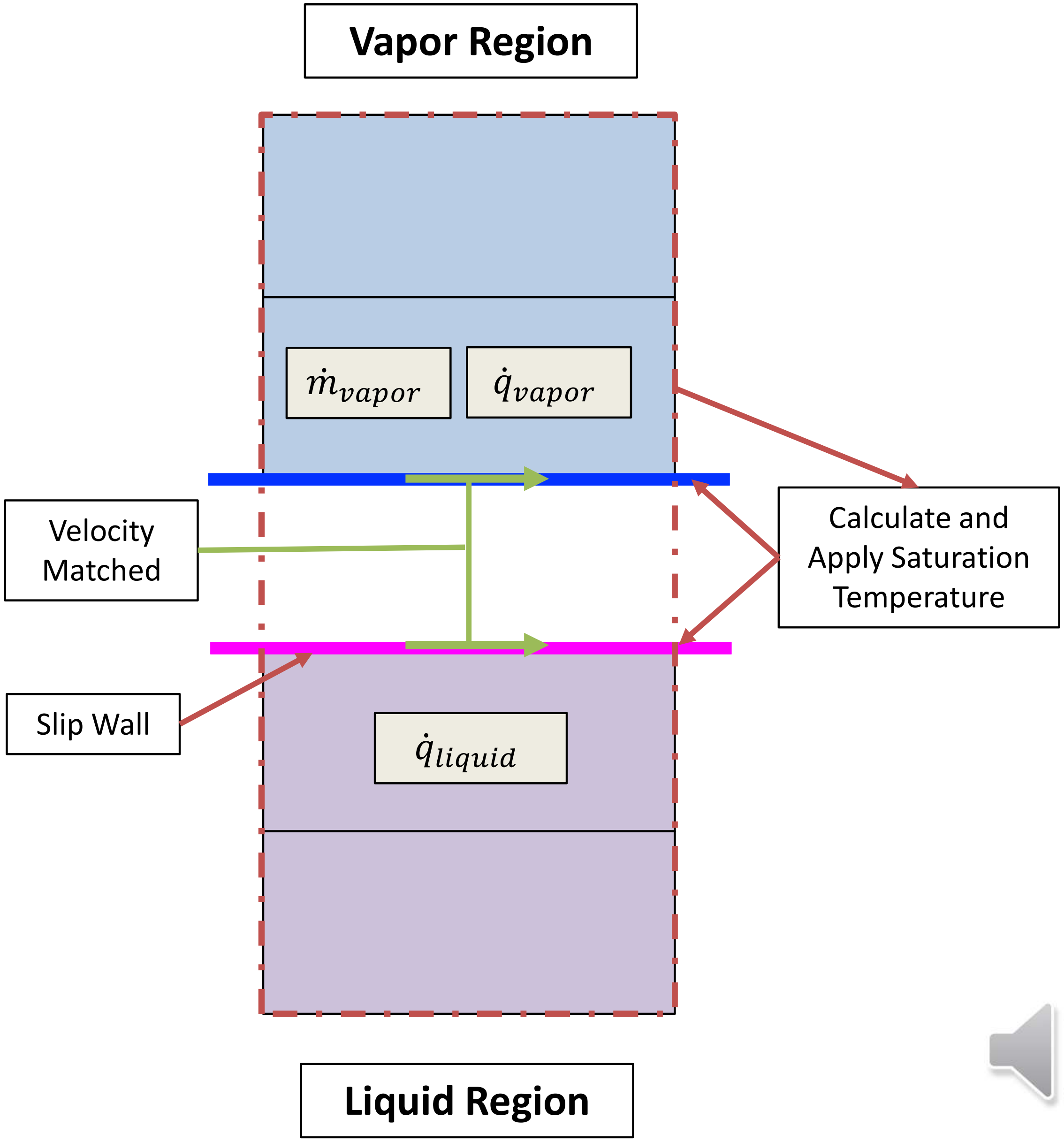
Sharp-Interface

- one set of gov. eqns.
  - across two single-phase regions
  - Phase interaction is enforced via boundaries
  - Mass transfer from energy balance at interface boundary
  - Like solving 1D heat equation with spatially varying properties.

---

1. Schrage RW. A theoretical study of interphase mass transfer. New York: Columbia University Press; 1953.
2. Mohammad Kassemi, et. al. “Validation of two-phase CFD models for propellant tank self-pressurization”

Sharp Interface Setup



Calculation flow, each timestep

$$T_{sat} = \left[\frac{1}{T_{ref}} - \frac{R}{LM} ln\left(\frac{P_{vapor}}{P_{ref}}\right)\right]^{-1}$$

$$\dot{m}_{vap} = \frac{Q_{IL} - Q_{IV}}{L}$$

$$\dot{q}_{vap} = \dot{m}_{vap} C_{p_{vap}} T_{sat}$$

$$\dot{q}_{liq} = -\dot{m}_{vap} C_{p_{liq}} T_{sat}$$

$$\boldsymbol{v}_{liq} \rightarrow \boldsymbol{v}_{vap}$$

Apply sources, update boundary

Solve gov. eqns.

Aside: Transient Error Metrics

- Quantitative metric to show the magnitude and phase difference between any two functions.
- ε_m is the difference in magnitude between two series
  - ε_m=1.0 means $F1 = {\sim}10 * F2$.
- ε_p is the difference in phase between two functions.
  - ε_p = 0.0 means no phase error, $\Phi_1 = \Phi_2$
  - ε_p = 1.0 means 100% out of phase, -cos(x) and cos(x)
- ε_c is an RMS combination of previous factors

$$A=\sum_{i=1}^{N} \mathrm{f}_1(i)^2$$

$$m=(A-B)/\sqrt{AB}$$

$$p=C/\sqrt{AB}$$

$$B=\sum_{i=1}^{N} \mathrm{f}_2(i)^2$$

$$\varepsilon_m=\operatorname{sign}(m)\operatorname{Log}_{10}(1+|m|)$$

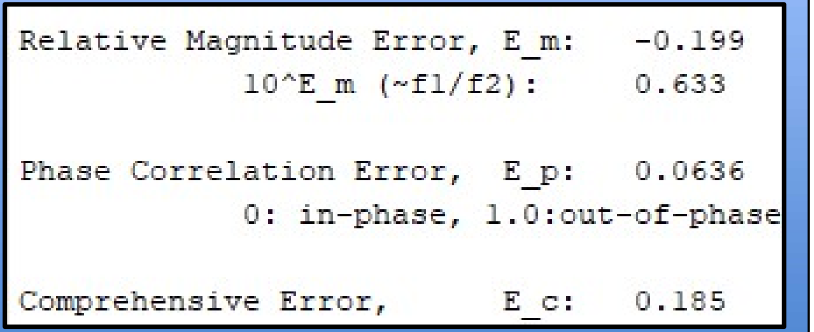
$$\varepsilon_p=\cos^{-1}(p)/\pi$$

$$C=\sum_{i=1}^{N} \mathrm{f}_1(i)\,\mathrm{f}_2(i)$$

$$\varepsilon_c=\sqrt{\frac{\pi}{4}\left(\varepsilon_m^2+\varepsilon_p^2\right)}$$

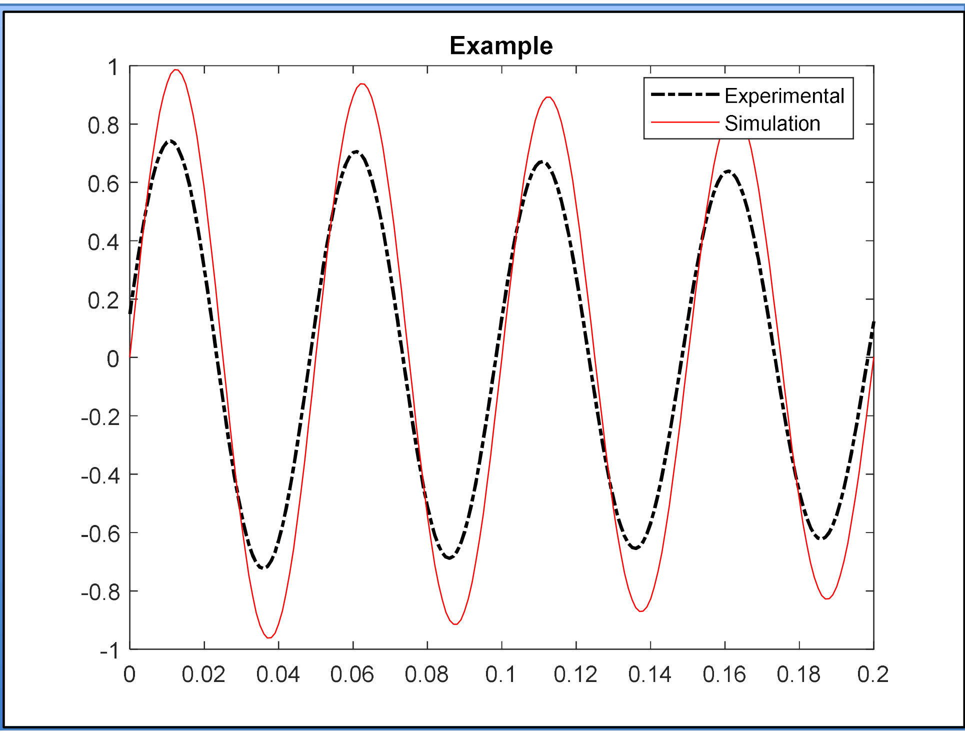
Simulation = $e^{-t}\sin(40\pi t)$

Experiment = $0.75e^{-t}\sin(40\pi t + 0.2)$

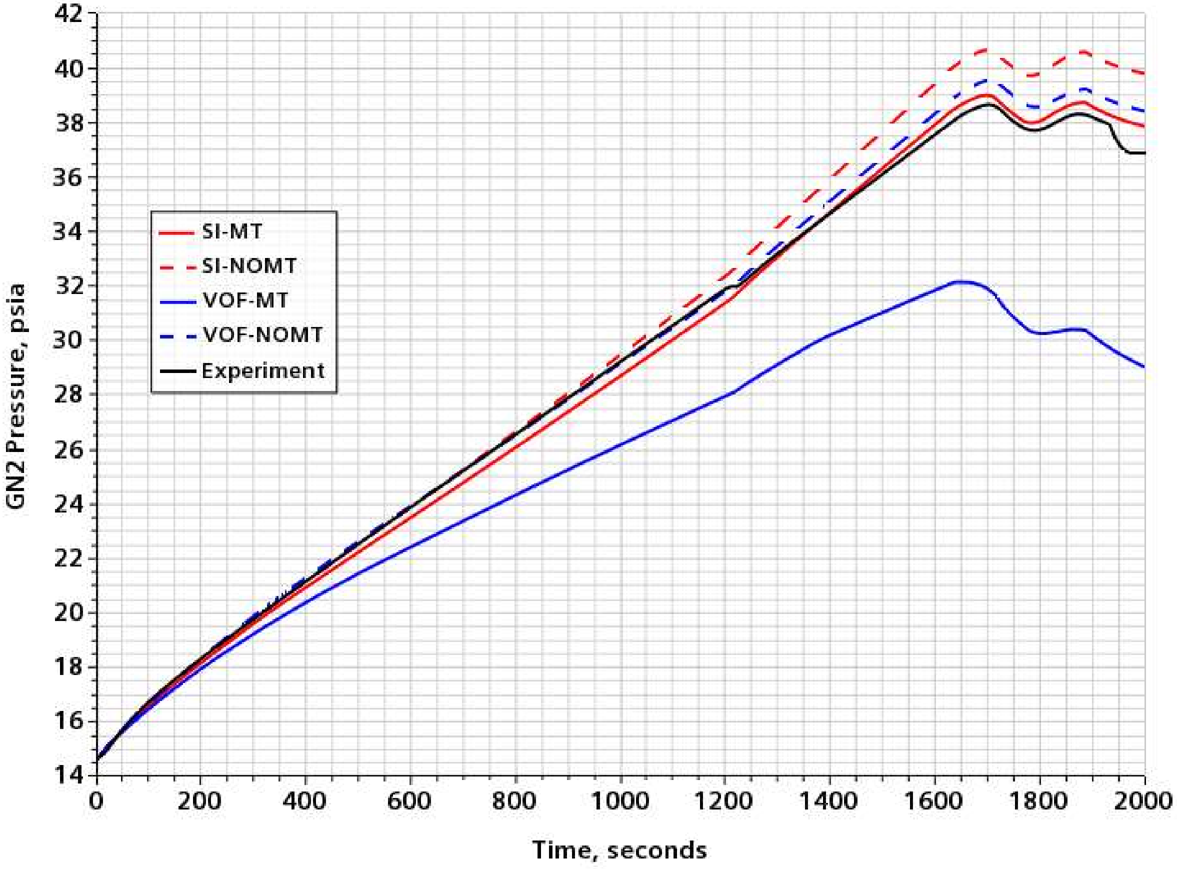


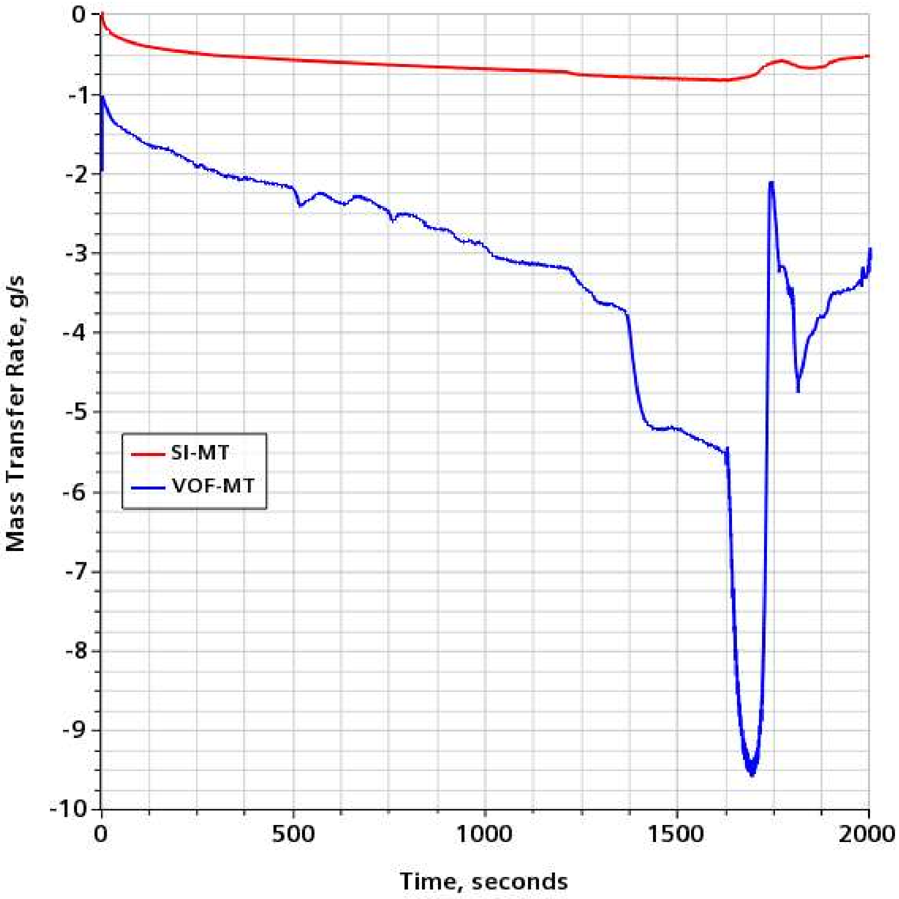
```
Relative Magnitude Error, E_m:    -0.199
           10^E_m (~f1/f2):       0.633

Phase Correlation Error,   E_p:   0.0636
           0: in-phase, 1.0:out-of-phase

Comprehensive Error,       E_c:   0.185
```

Russell, D.. “Error Measures for Comparing Transient Data : Part I : Development of a Comprehensive Error Measure Part II : Error Measures Case Study.” (2000).



CFD Results – Pressure Trace

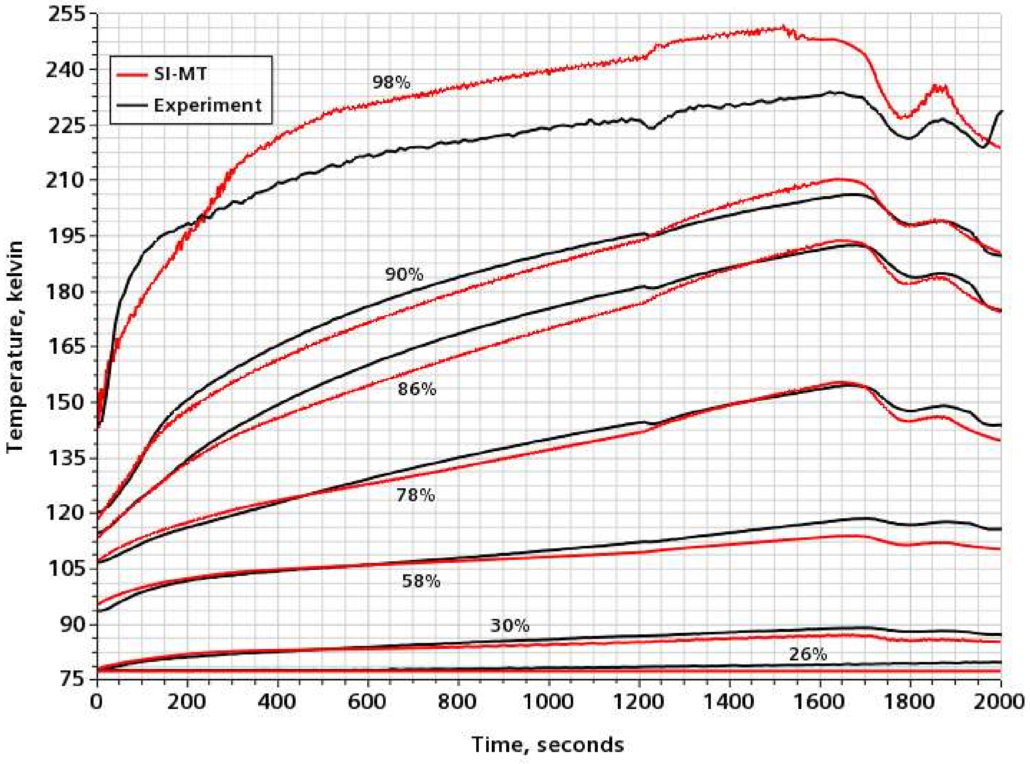


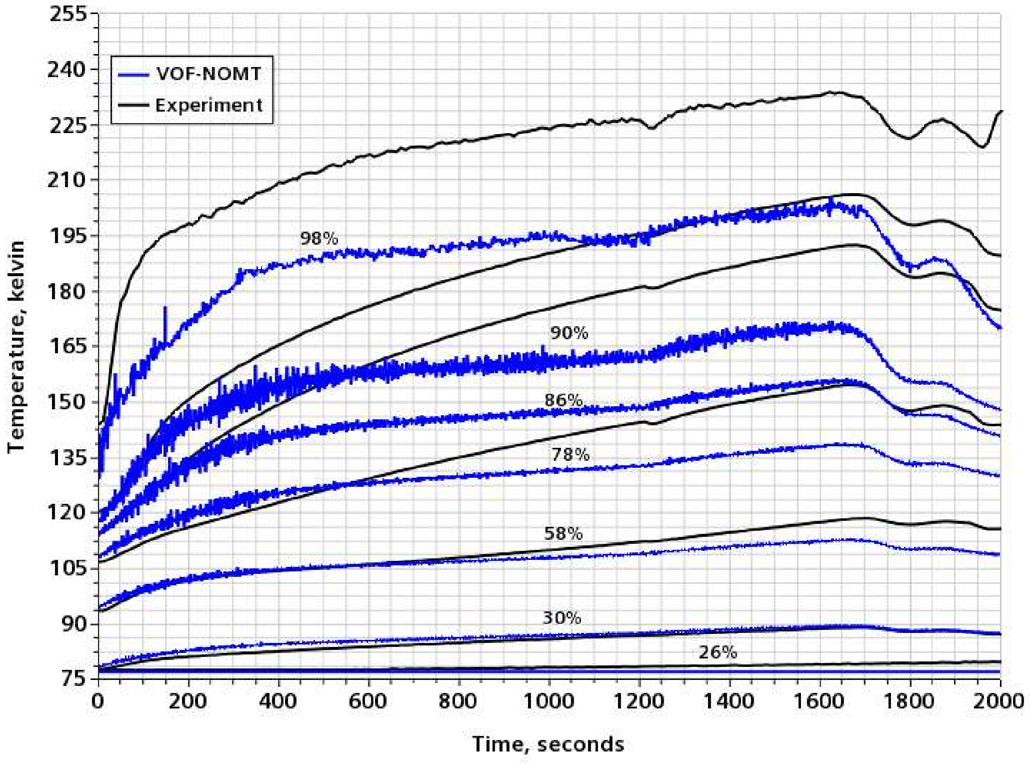


Abbreviation	Multiphase Model	Phase Change?
SI-MT	Sharp Interface	Yes
SI-NOMT	Sharp Interface	No
VOF-MT	Volume of Fluid	Yes
VOF-NOMT	Volume of Fluid	No

	SI-MT	SI-NOMT	VOF-MT	VOF-NOMT
ε_m	0.006	0.033	-0.117	-0.006
$\lvert 1 - 10^{\varepsilon_m} \rvert$	1.4%	7.9%	24%	1.4%
ε_p	0.004	0.007	0.018	0.004
ε_c	**0.006**	0.030	0.105	**0.007**

CFD Results – Temperature Profile by Volume





ε_c	26%	30%	46%	58%	70%	78%	82%	86%	90%	94%	98%	Mean
SI-MT	0.001	0.010	0.027	0.015	0.009	0.007	0.015	0.012	0.006	0.008	0.038	**0.013**
VOF-NOMT	0.054	0.076	0.145	0.196	0.246	0.282	0.303	0.326	0.359	0.407	0.426	0.256

Conclusion

- A sharp interface (SI) model was developed using STARCCM+ that solves two single phase domains simultaneously and links them via an energy balance at their shared boundary.
- The SI model predicts the pressure trace and temperature stratification from the EDU pressurization experiment with excellent agreement

- While SI doesn’t work out of the box as VOF does, the increase in accuracy is well justified.
  - Equivalent case using VOF model required 26x the computational resources
- Work is ongoing to further develop the SI model for complex moving interfaces for microgravity analysis and the inclusion of additional physics

- For more details on SI setup and results, please refer to the paper.