Initial Computational Analysis of Helium Subsurface Pressurization

Jacob Brodnick – NASA MSFC ER42
Jason Hartwig – NASA GRC LTF0

Presented By
Jacob Brodnick

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Background

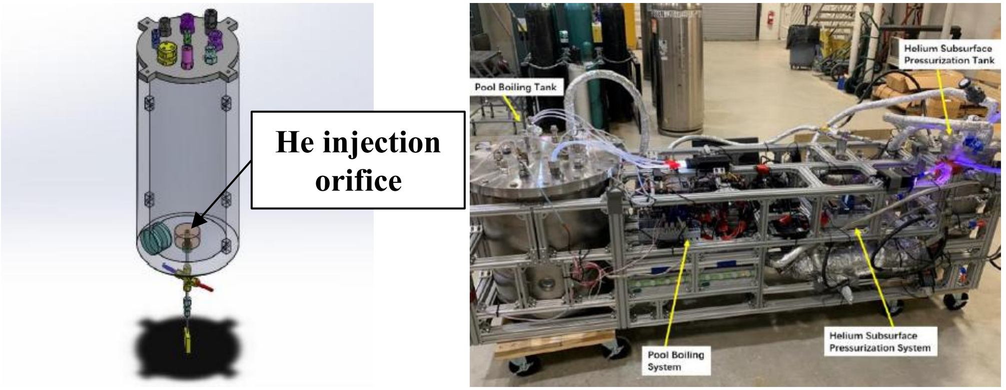
- Helium subsurface pressurization (HSP) in low gravity was simulated using computational fluid dynamics (CFD) analysis.
- Pressurant flow regime characteristics were compared to imagery taken from a parabolic flight experiment conducted under a NASA Flight Opportunities grant, FO 244-P [1].
- Initial results are shown herein while a more comprehensive validation effort will be documented in the future.
- Validation of HSP dynamics is intended to help inform future trade studies of tank pressurization for spacecraft engine restarts and propellant transfer.
  - Efficient methods of pressurizing directly into a cryogenic propellant are sought.
  - Additionally, HSP has been shown to thermally condition cryogenic propellants which may be leveraged in future in-space operations.

Experiment Description

- HSP was conducted on the ground and in flight using the hardware shown
  - 30 parabolas were flown over two flights
- Pressurant was injected into an 8.34 L liquid nitrogen (LN2) tank via an orifice
  - Pressurant flow rate and temperature along with orifice diameter were varied
- Tank was filled and continuously vented to 101.3 kPa prior to flight
- A viewport was used to directly image the bubble dynamics during pressurization
- Pressurant dynamics were categorized into flow regimes

Submerged Pressurization Test Configuration [1]

Left: Tank CAD / Right: Parabolic Flight Test Article



Measured Flow Regime Map [1]

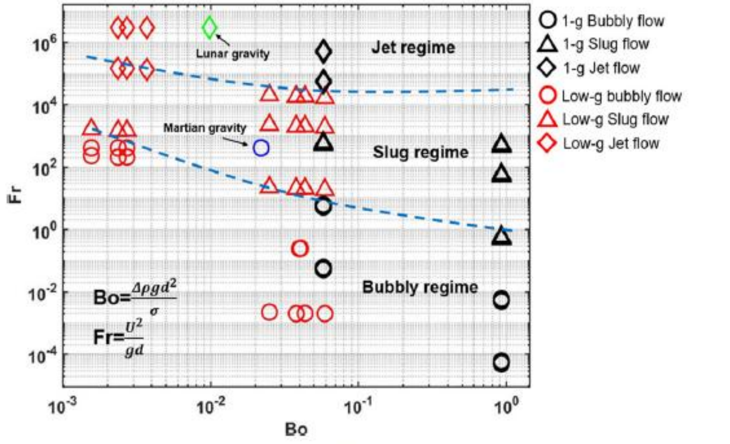


Fig. 12 | Two-phase flow regime map. All gravity levels two-phase flow regime map.

Simulation Setup

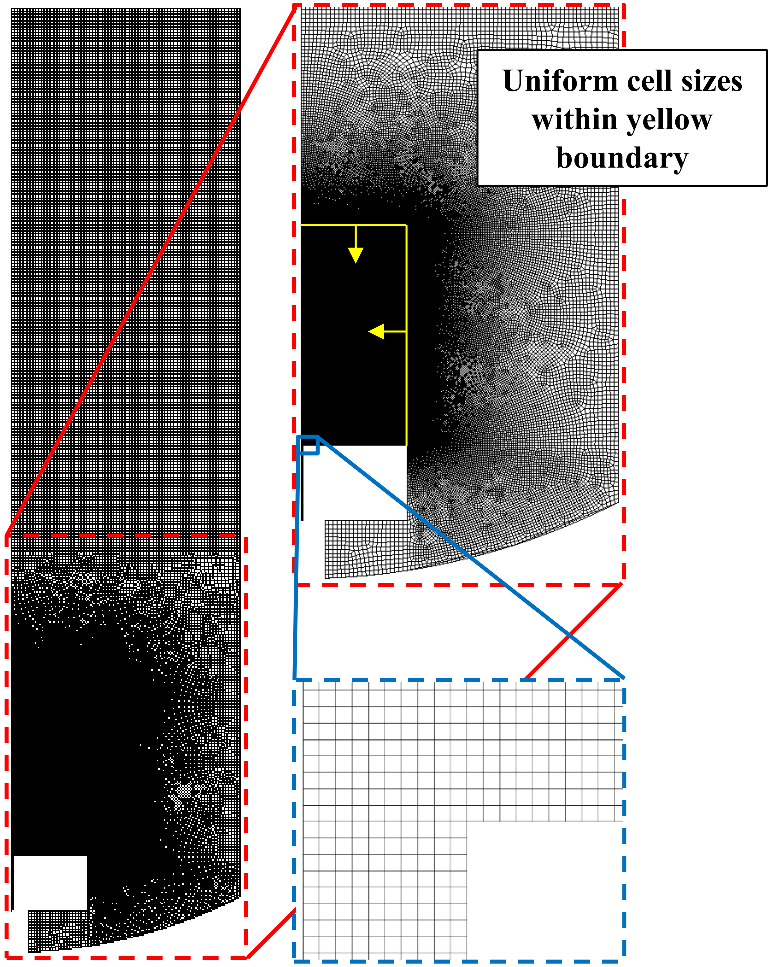
- Loci-Stream-VoF solver [2]
  - All-speed pressure-based solver
- Solver settings:
  - Unsteady 1st order spatial and temporal accuracy
  - Compressible gas with incompressible liquid
  - Boussinesq approximation of natural convection
  - Turbulent RANS k-w SST 2003 with interfacial turbulent damping
  - Surface tension and contact angle
  - Volume of Fluid (VoF) model with geometric reconstruction type of interface tracking
  - Phase change excluded in initial simulations, may be impactful in flow regime transitions

Model Geometry

Modeled tank was smaller than test article, correcting model for future validation

Computational Mesh

Initial simulations were axisymmetric to facilitate rapid sensitivity study



Simulated Conditions

- Two test cases were selected initially to begin identifying modeling methodology and numerical convergence criteria for capture of HSP dynamics
- A high and middle flow rate condition are highlighted in the reported flight test matrix [1]

Flight Test Matrix [1]

Test Number	Orifice Diameter (mm)	Gravity Level (g/g_o)	Inlet Temp (K)	Inlet Mass Flow Rate (kg/s)
2-1	1	0.038	185	2.73E-07
2-2	1	0.042	186	2.73E-06
2-3	1	0.035	247	8.18E-06
2-4	1	0.043	200	2.73E-08
2-5	1	0.031	214	2.73E-06
2-6	1	0.041	255	8.18E-06
2-7	1	0.041	230	2.73E-09
2-8	1	0.029	172	2.73E-07
2-9	1	0.047	218	2.73E-09
2-10	1	0.044	198	2.73E-08
2-11	1	0.025	260	8.18E-06
2-12	1	0.027	208	2.73E-09
2-13	1	0.032	182	2.73E-07
2-14	**1**	**0.046**	**208**	**2.73E-06**
2-15	1	0.064	230	2.73E-09
2-16	**1**	**0.051**	**170**	**2.73E-07**
2-17	0.25	0.031	196	2.73E-09
2-18	0.25	0.039	215	2.73E-07
2-19	0.25	0.045	207	8.18E-06

Simulated Conditions

← High Flow Rate Case (2-14)

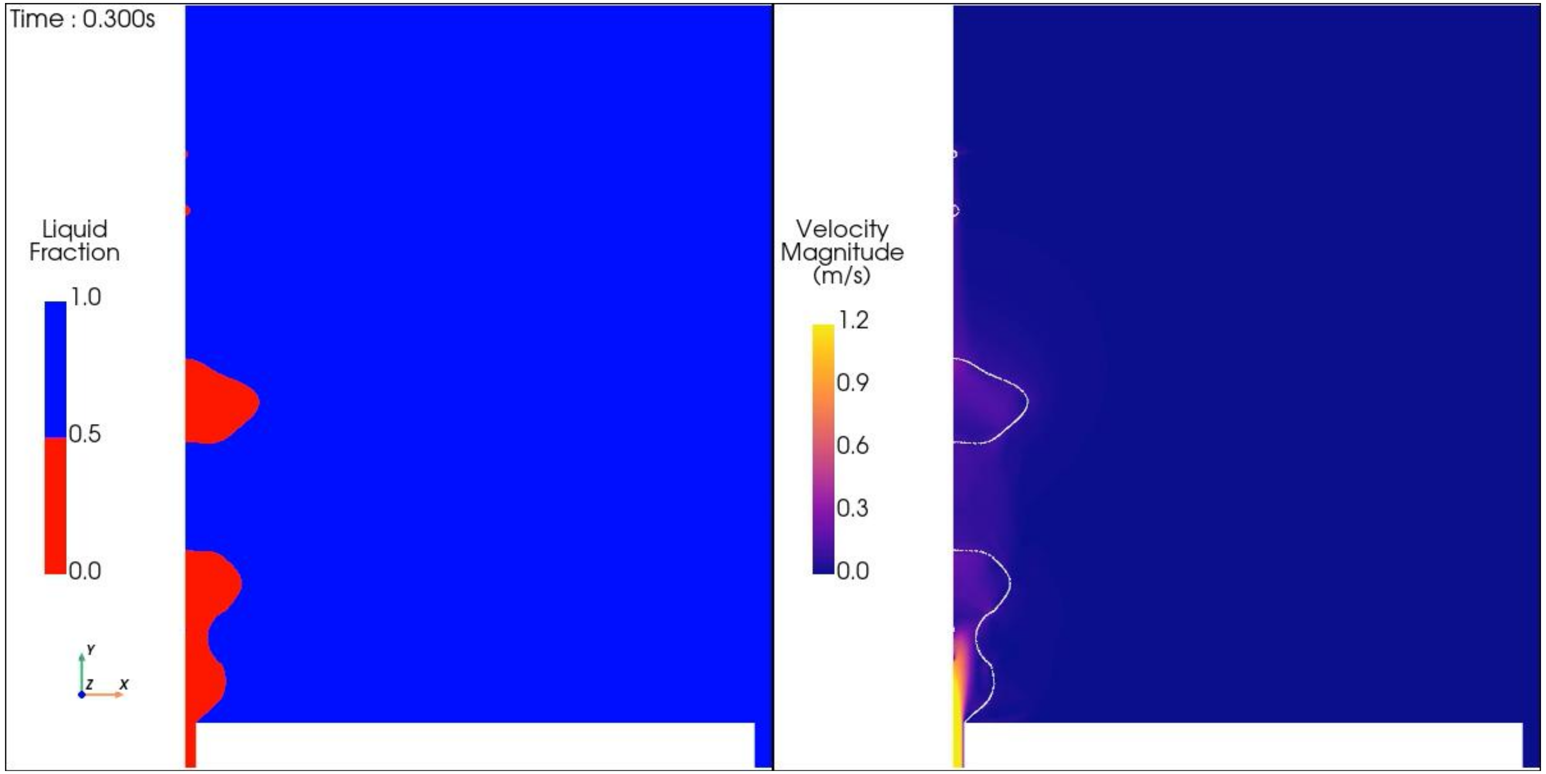
← Middle Flow Rate Case (2-16)

Results – Middle Flow Rate Case

- Nominal simulation results for test case 2-16 are shown
- Distinct bubbles form and detach as buoyancy overcomes surface tension near the orifice-tank interface
- Following detachment, bubble growth from the orifice can exceed detached bubble convection causing two bubbles of combine
- The resulting dynamics often imparted momentum into the combined bubble such that further bubble combination was not observed

Animation of Simulated Pressurant Dynamics

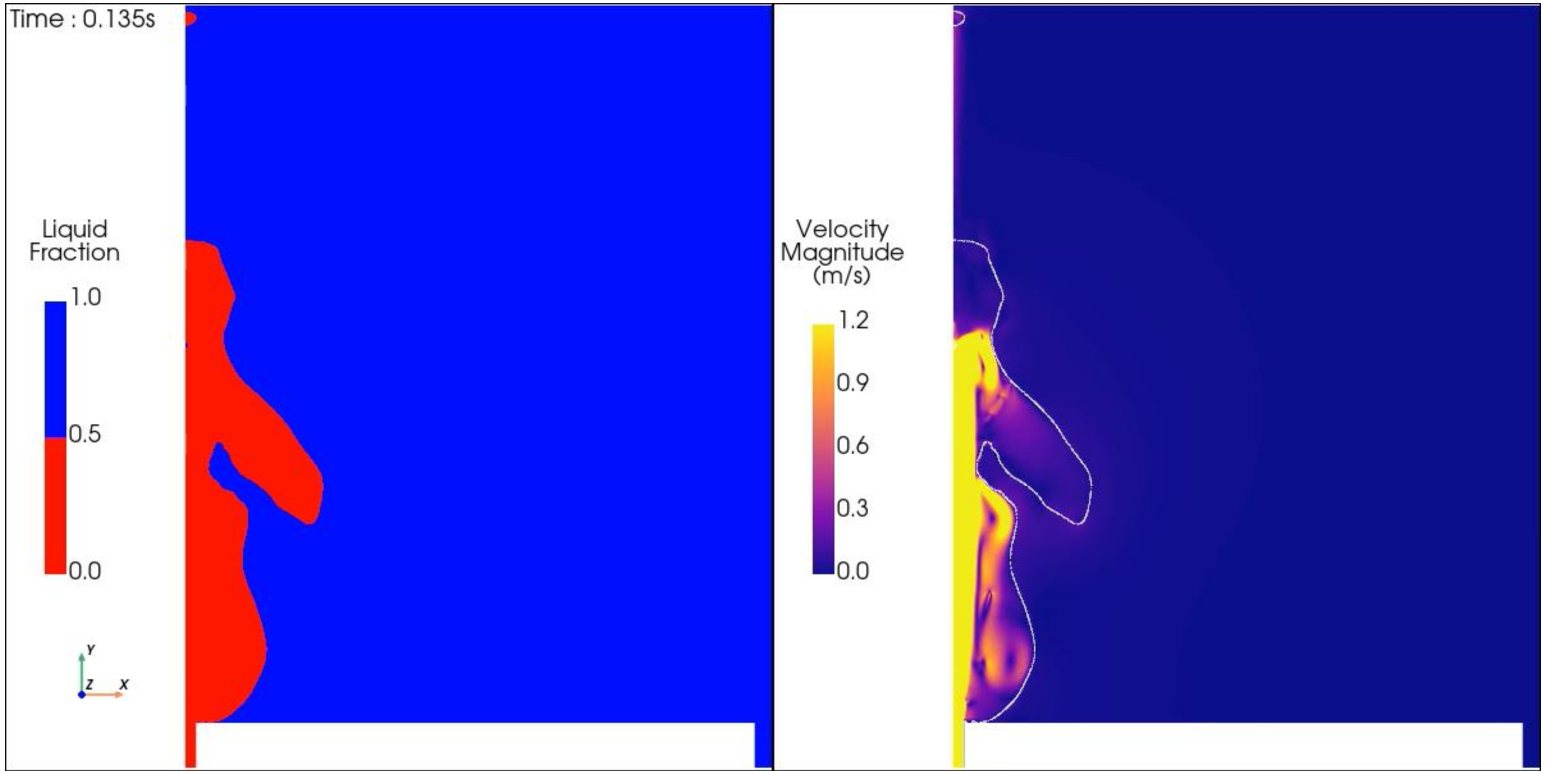
Case 2-16



- Nominal simulation results for test case 2-14 are shown
- No distinct bubble formation was observed
- Pressurant momentum significantly exceeded buoyancy driven convection resulting in more chaotic bubble formation, detachment, and combination
- Periodic bubble detachment was observed but rapid bubble recombination makes the resulting structure look continuous with periodic bulges

Animation of Simulated Pressurant Dynamics

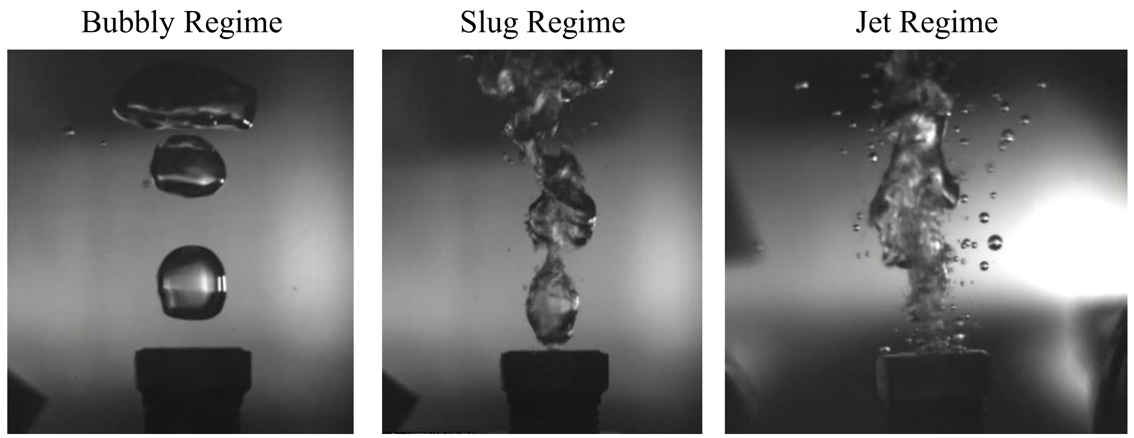
Case 2-14



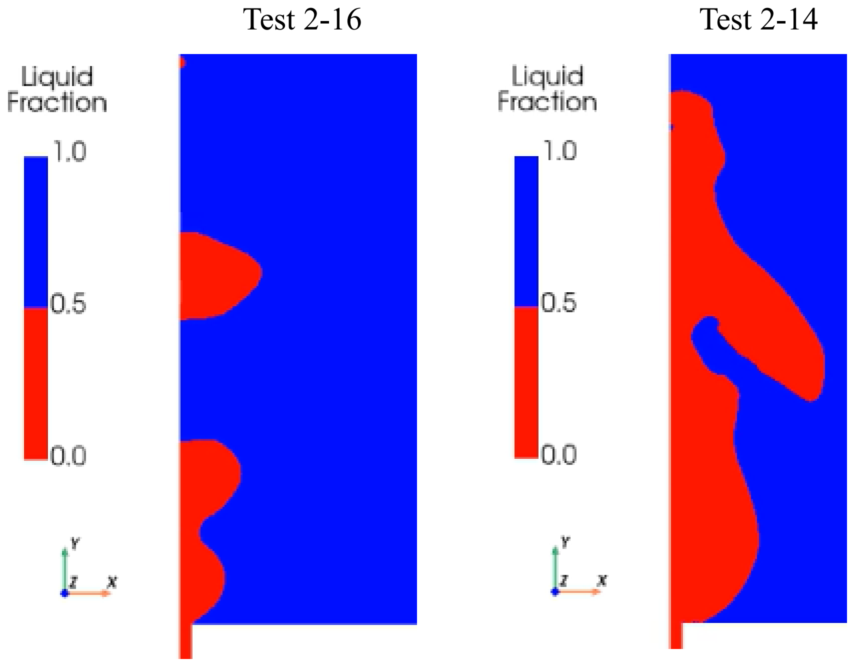
Results – Flow Regime Comparisons

- Multiple flow regimes were identified in testing which are shown below
- Predicted flow regimes correspond well to experimental observations, but quantitative comparison of transition regions is still in-work
  - Case 2-16 (middle flow rate): bubbly-to-slug flow transition
  - Case 2-14 (high flow rate): slug regime

Low-g Bubble Detachment Visualization Data [1]



Low-g Bubble Detachment Analysis Snapshots



Conclusion

- Initial CFD simulation results of low-g HSP in a small LN2 tank were predicted.
- Predicted flow regimes included (1) distinct bubble formation and (2) periodic bubble detachment and combination which correspond well to experimental observations.
- Quantitative comparison of transition regions between flow regimes is still in-work.
- The present analysis is a part of a concerted effort to better understand if subsurface pressurization is viable or optimal for any applications or parameter spaces in future NASA missions.

Forward Work

- Include phase change in CFD simulations
- Demonstrate mesh and mass transfer convergence
- Demonstrate contact angle sensitivity
- Expand the simulated set of test conditions
- Compare bulk liquid cooling predictions to test measurements

References

1. Jinze Yu, et. al., "Cryogenic helium subsurface pressurization in terrestrial and low-gravity: experiments and flow visualization," Microgravity Journal Paper, 2025.
2. https://www.snumerics.com/