Validation of a Multiphase Computational Fluid Dynamics Model for Vapor Pull-Through in Normal and Low Gravity

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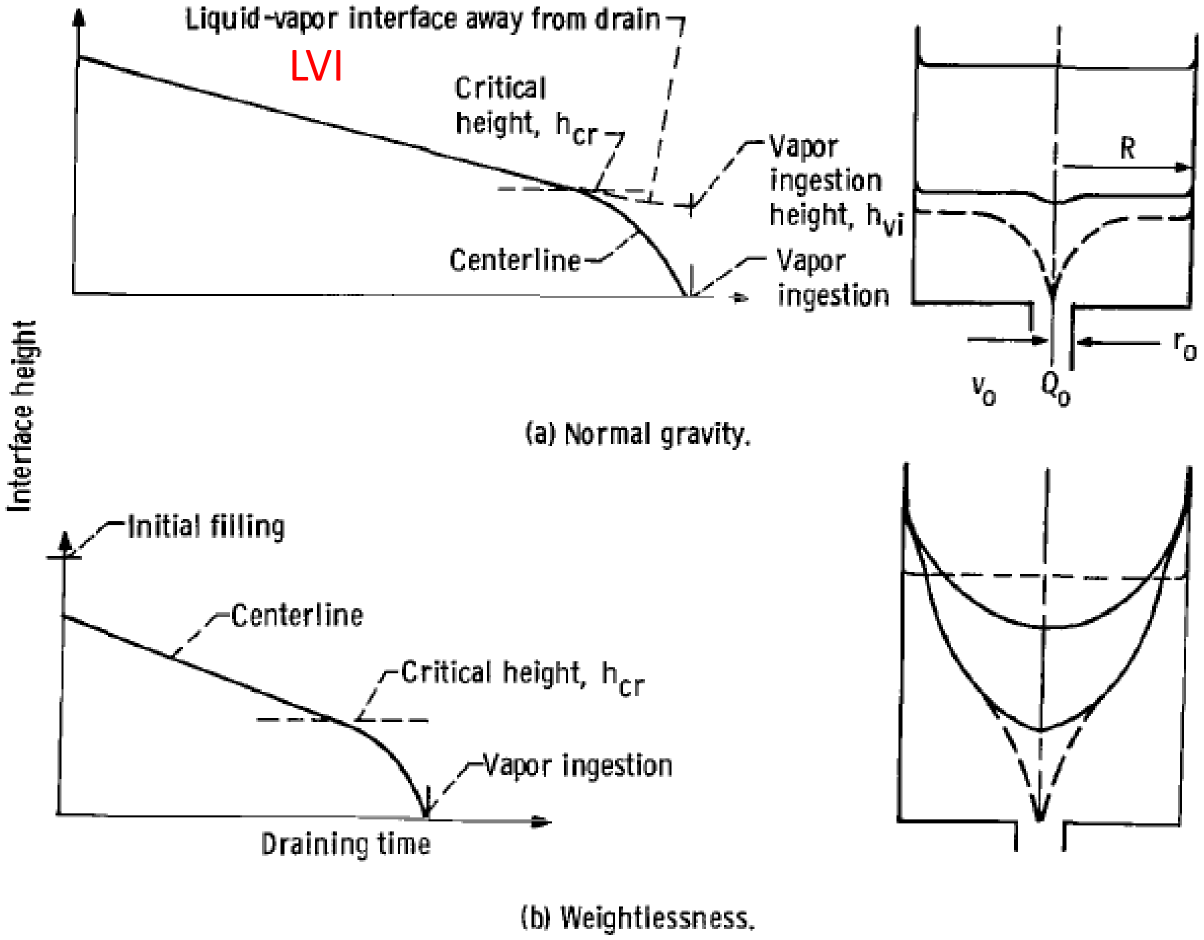
Motivation

- On-orbit cryogenic propellant depots for refueling spacecraft can support and enable NASA's long-duration deep space missions
  - Human Landing System (HLS)
  - Nuclear Thermal Propulsion (NTP)
  - Liquefaction/ISRU in reduced gravity
- Vapor Pull-Through (VPT) is important to understand for designing propellant transfer systems and engine operation
  - VPT during engine operation can lead to failure
  - Pressure-fed tank-to-tank transfer: VPT will decrease flow rate and increase transfer duration
- Accurate Computational Fluid Dynamics (CFD) models can be used to design hardware and CONOPs for transfer vehicles, thereby reducing system and propellant mass
- CFD models validated to experimental data in relevant environments will improve confidence in predictions

Artist rendering of on-orbit refueling with SpaceX Starship. Credit: SpaceX

VPT (or Vapor Ingestion) Phenomenon

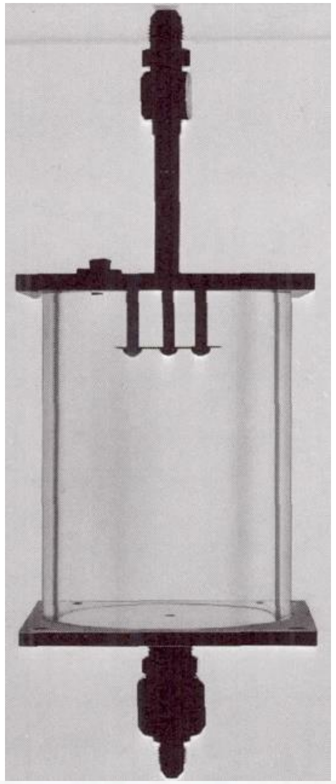
- VPT, or vapor ingestion, is defined as the moment when vapor is ingested into the outlet feedline while draining a tank
- Critical Height and Vapor Ingestion Height
  - h_{cr} is the centerline LVI height at the incipience of VPT
  - h_{vi} is the near-wall LVI height when VPT occurs
- Normal Gravity (1g)
  - High Bond number
  - Interface remains flat while draining
  - VPT defined by h_{cr} and h_{vi}
  - Small liquid residuals
- Low Gravity
  - Low Bond number
  - Interface is curved while draining
  - VPT defined by h_{cr} only
  - Large liquid residuals

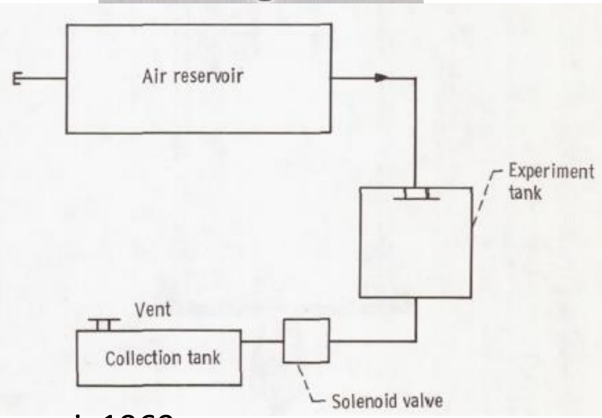


[1] Abdalla and Berenyi, 1969

Drop Tower Experiment

- Abdalla and Berenyi [1-2] conducted VPT tests in the late 1960s and early 1970s for flat- and hemispherically-bottomed tanks in normal and low gravity
- Low-g experiments conducted in the 2.2 Second Drop Tower (<0.001g) at NASA Lewis Research Center (now NASA Glenn)
- Acrylic plastic, flat-bottomed tank with baffle to mitigate interface impingement
- Working Fluids: Ethanol, Trichlorotrifluoroethane, Ethane/Glycerol mix
- Tank Diameters of 4 & 8 cm, Outlet Diameters of 0.2, 0.4, and 0.8 cm
- Tested a range of outflow rates (V_o ~ 2 – 95 m/s)
- Drop Tower Test Operation:
  1. Ullage pressurized using air reservoir for a specified outflow
  2. Solenoid opened once curved interface centerline reached low point on first pass through equilibrium
  3. High speed camera measured interface height as a function of time
- **Objective: Develop correlations to characterize VPT**
  – 1g: h_{vi} and residual liquid vs. Froude# $Q_o^2/_{gR^5}$
  – Low-g: h_{cr} and residual liquid vs. Weber# $Q_o^2/_{\beta R^3}$

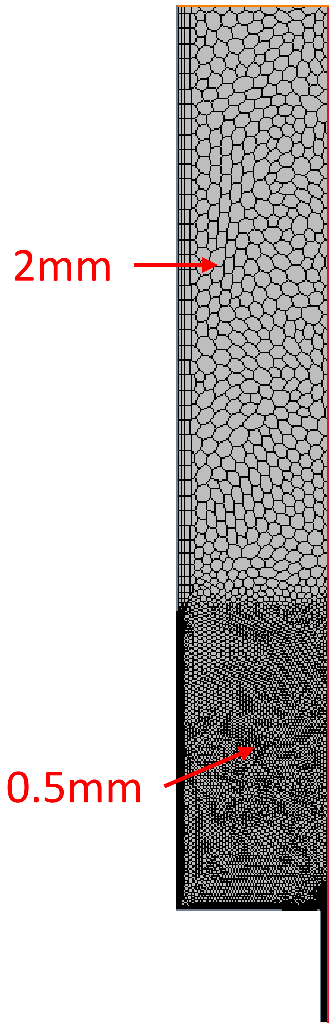


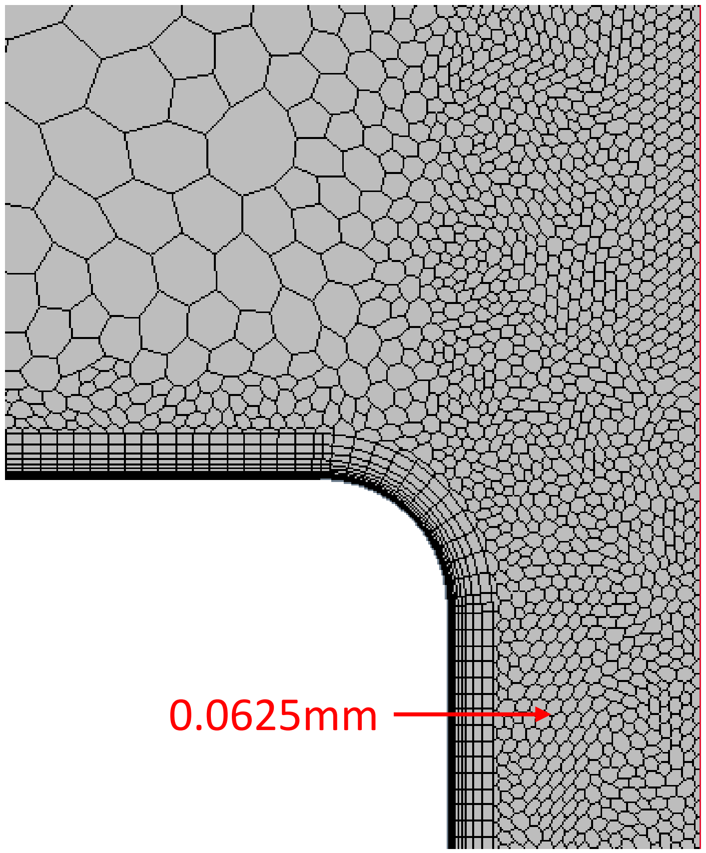


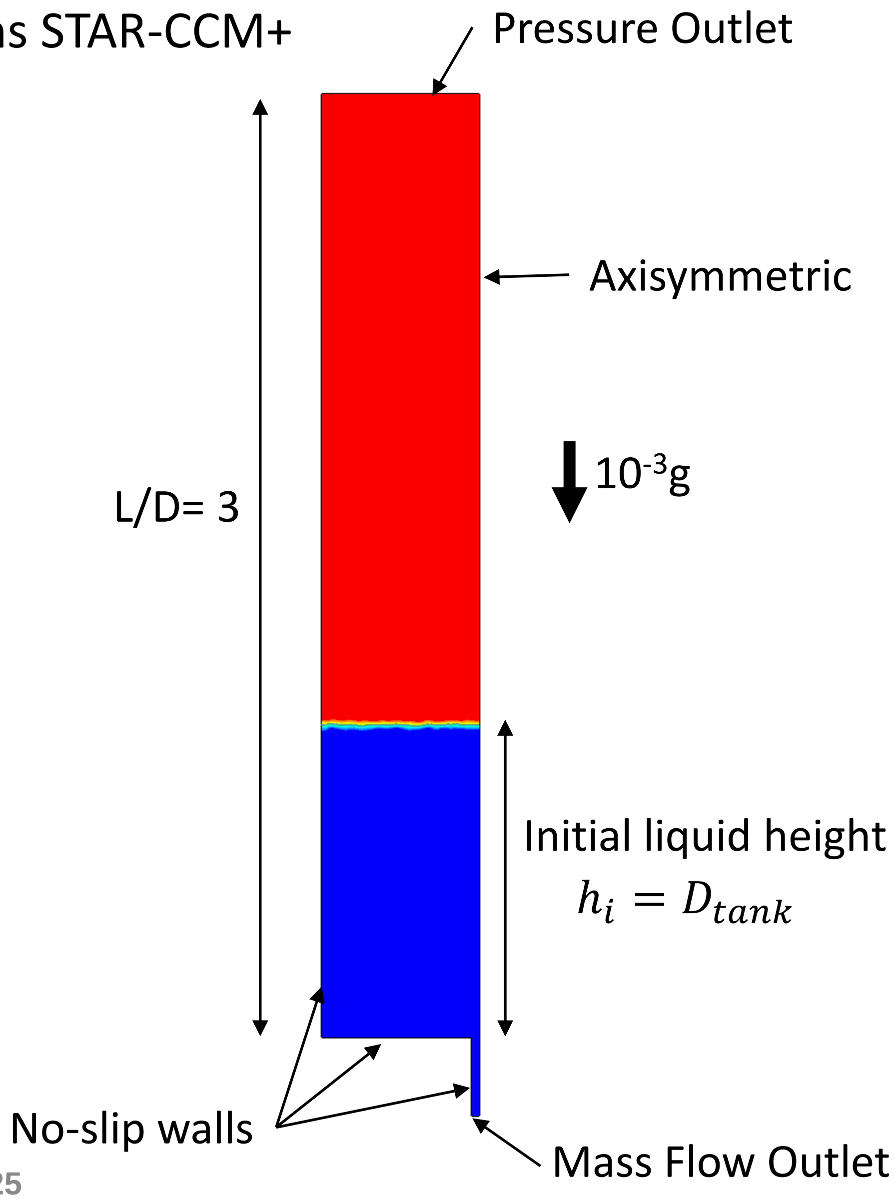
[1] Abdalla and Berenyi, 1969

Computational Model: Geometry/Mesh and Boundary Conditions

Simulations run using commercial CFD code Siemens STAR-CCM+







Computational Model: Physics Models

- 2D-axisymmetric and 3D
- Volume-of-Fluid Multiphase Solver
- Surface Tension Force via Continuum Method by Brackbill [3] with 0deg contact angle
- Incompressible liquid and vapor (Ethanol and Air); heat transfer neglected
- Realizable k-ε Two-Layer All y+ Turbulence model

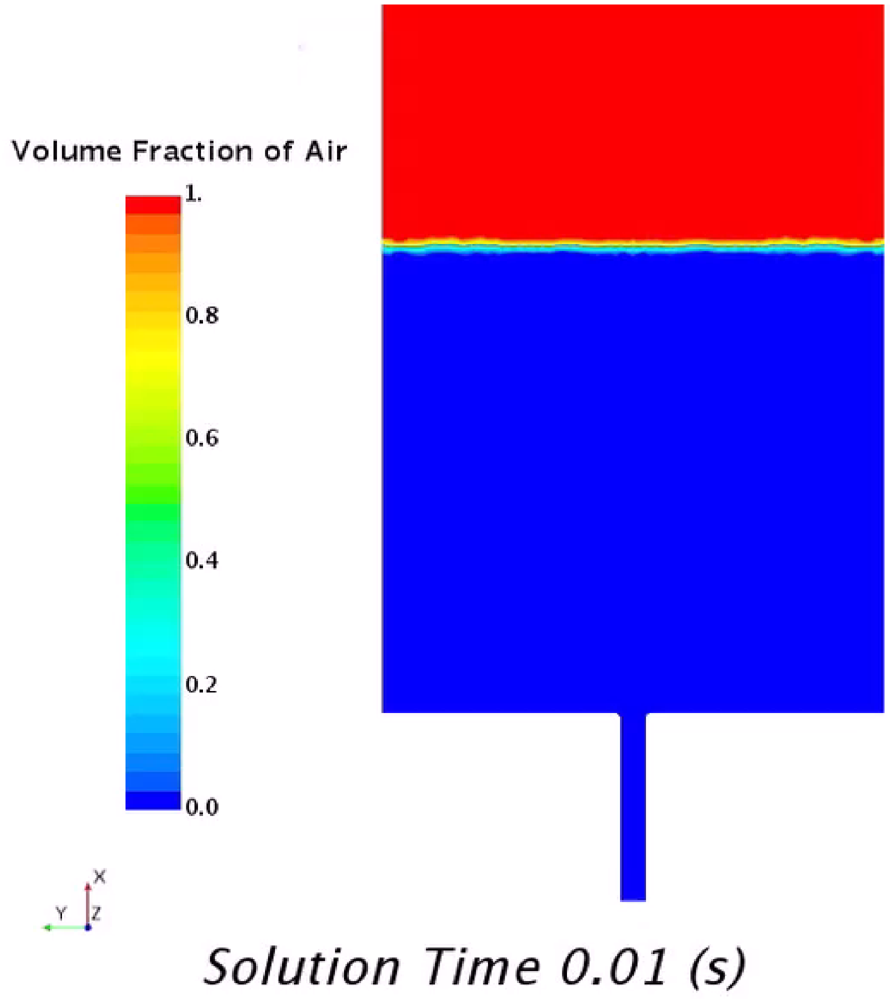
Fluid Properties

Liquid	Surface Tension, σ, N/m	Density, ρ, kg/m^3	Viscosity, μ, Pa-s
Ethanol	0.0223	789	0.0012
Trichloro-trifluoro-ethane	0.0186	1580	0.0007
60 Ethanol - 40 Glycerol (% by volume)	0.0269	988	0.0154

CFD Case Summary

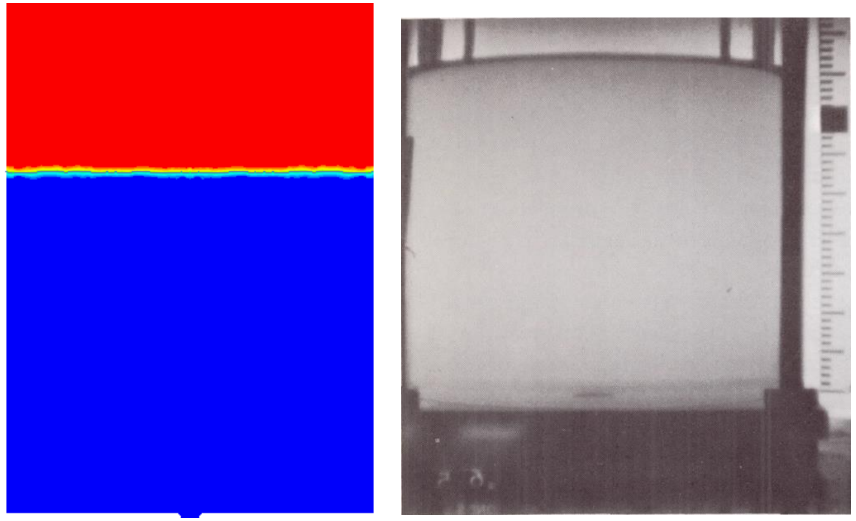
Outflow Velocity, V_o (m/s)	Tank Radius, R (cm)	Outlet Radius, r_o (cm)	Liquid
2	2.0	0.2	Ethanol
10.08	2.0	0.1	Ethanol
16.88	2.0	0.1	Ethanol
20.80	2.0	0.1	Ethanol
25	2.0	0.1	Ethanol
35	2.0	0.1	Ethanol
55	2.0	0.1	Ethanol

V_o = 10.08 m/s, 1g



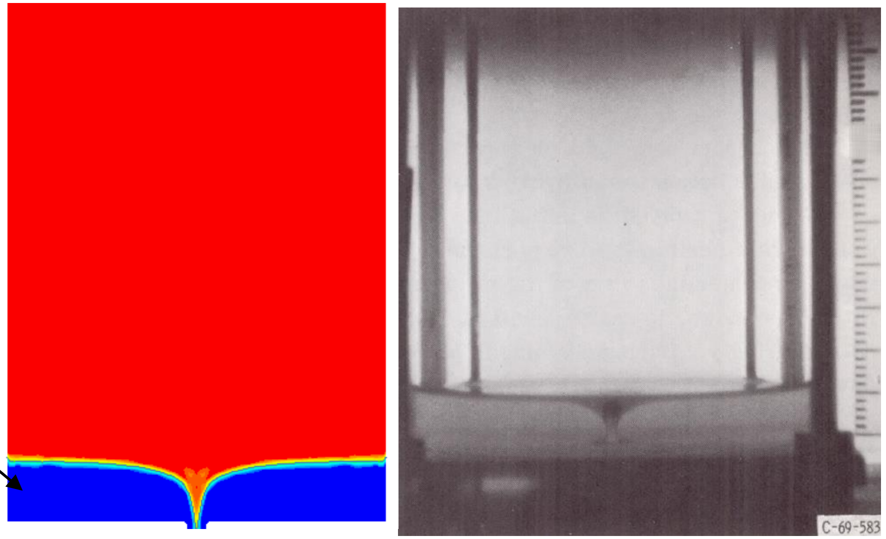
$$Bo = \frac{\Delta\rho g D^2}{\sigma} = 554$$

Initiation of Draining



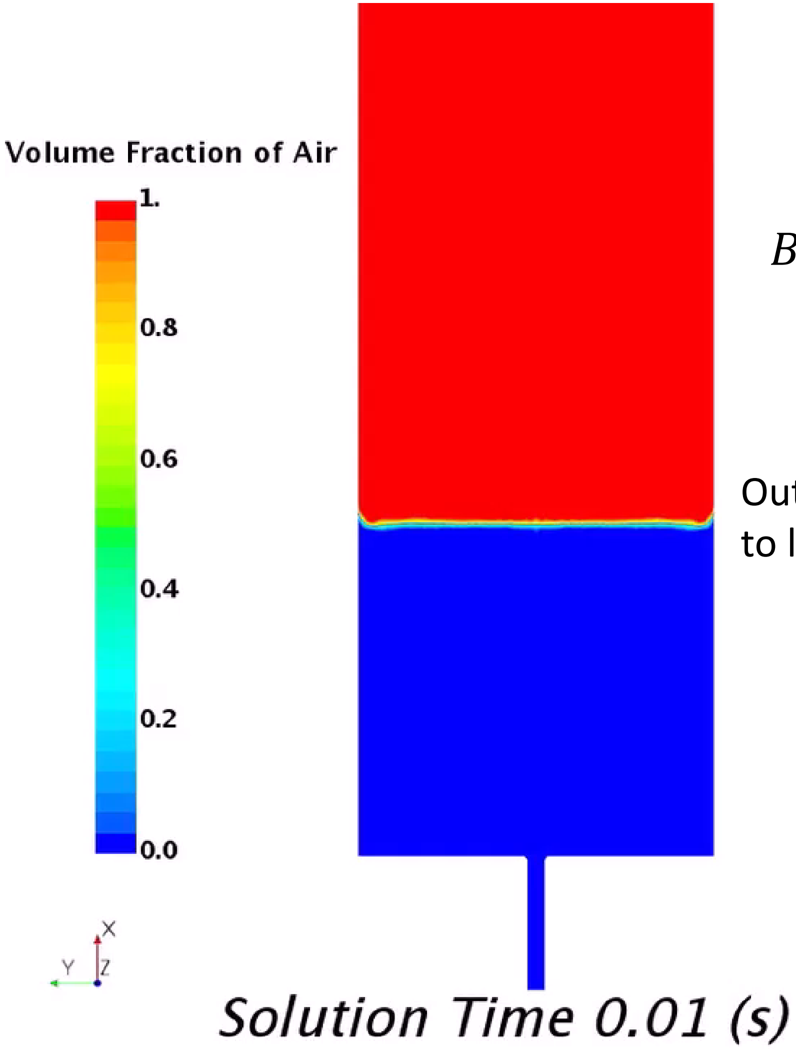
Vapor Ingestion

Small residual



Qualitative Comparison to Experiment: Low Gravity

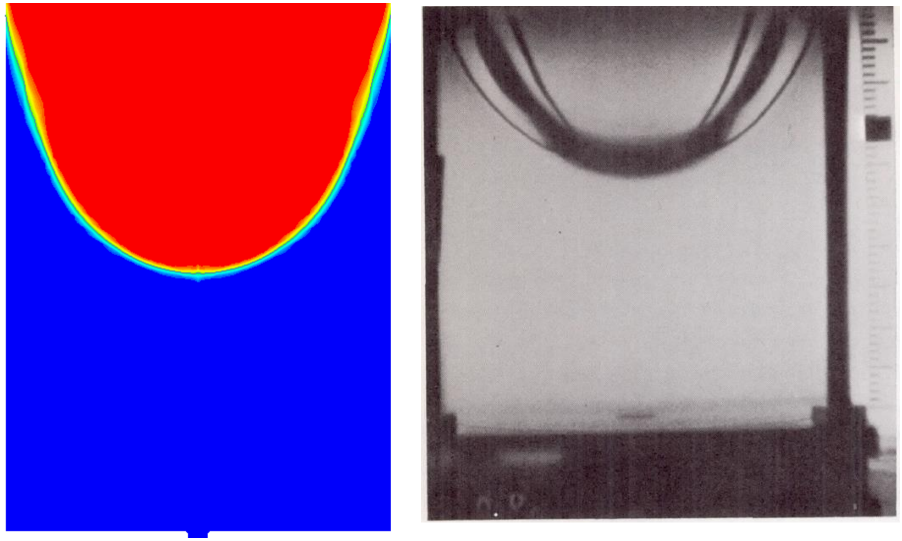
V_o = 10.08 m/s, 10^{-3}g



$$Bo = \frac{\Delta \rho g D^2}{\sigma} = 0.05$$

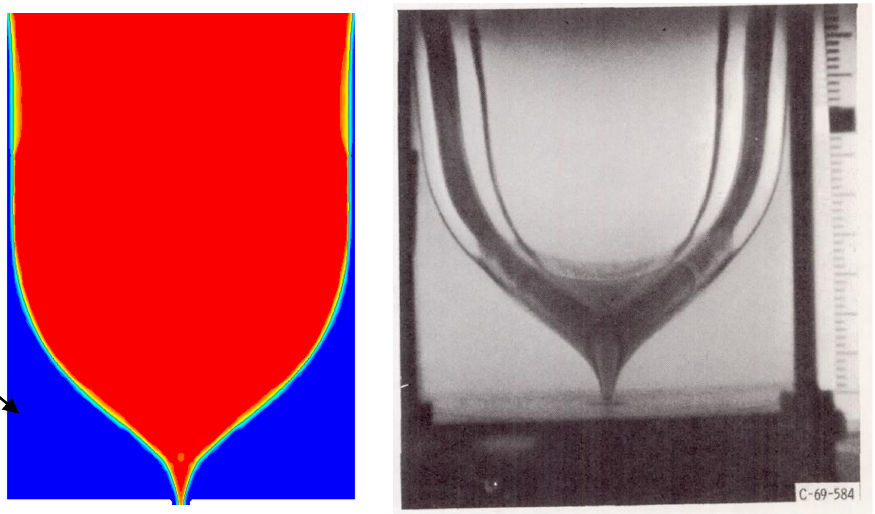
Outlet flow begins at $t = 0.4s$ to let interface reach low point

Initiation of Draining



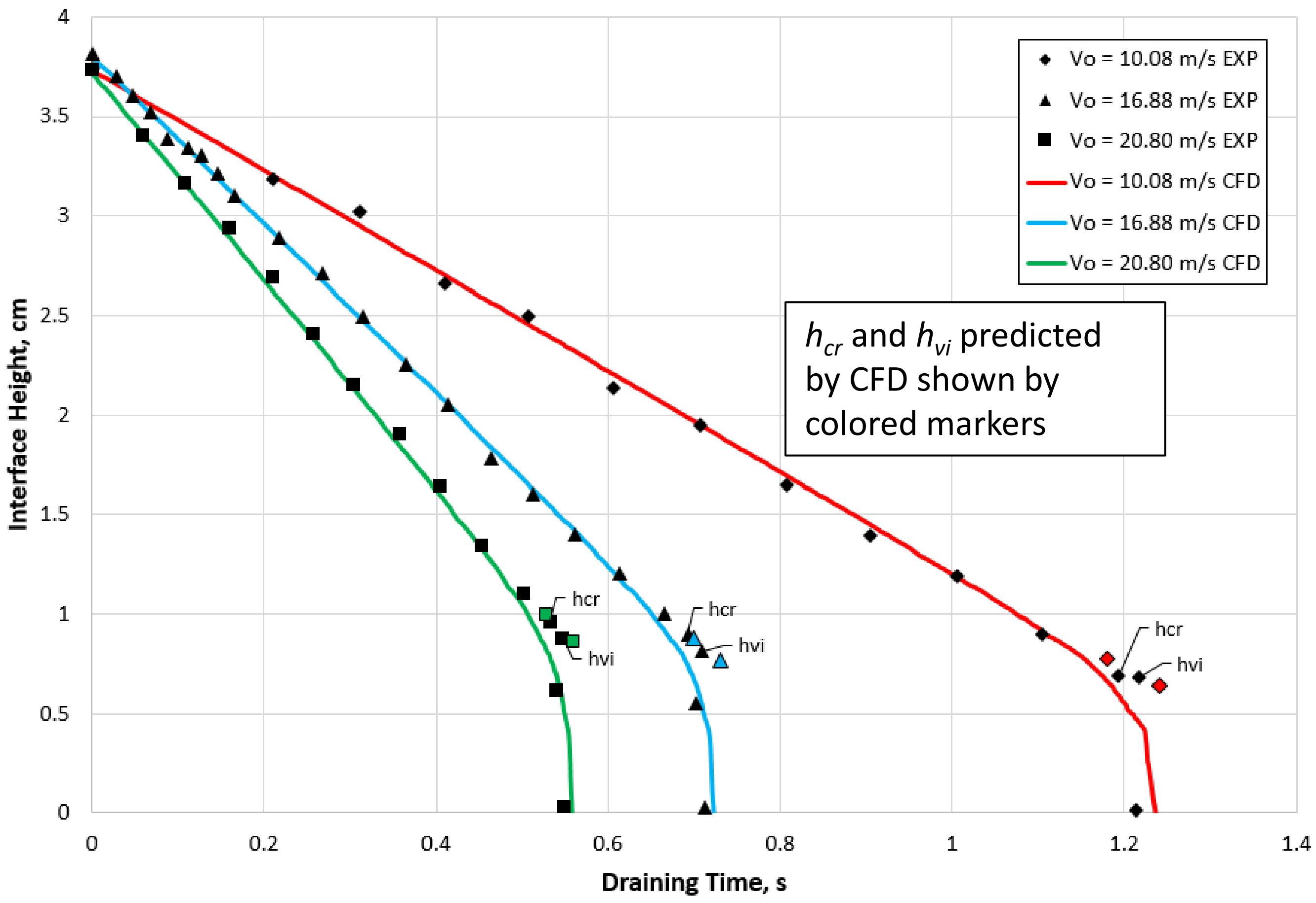
Vapor Ingestion

Large residual



Draining Curves: Normal Gravity

- Centerline interface height reported for 3 outflow velocities
- CFD shows good agreement to experiment
- Some oscillation of liquid-vapor interface observed in experiment for low velocity case



Critical and Vapor Ingestion Heights 1g (all heights in cm)

V_o, m/s	h_{cr} EXP	h_{cr} CFD	% error	h_{vi} EXP	h_{vi} CFD	% error
2	NR*	0.70	-	0.45	0.55	22.2
10.08	0.69	0.78	12.4	0.68	0.64	6.4
16.88	0.90	0.88	1.9	0.82	0.76	6.2
20.80	0.96	0.99	3.3	0.88	0.86	2.3

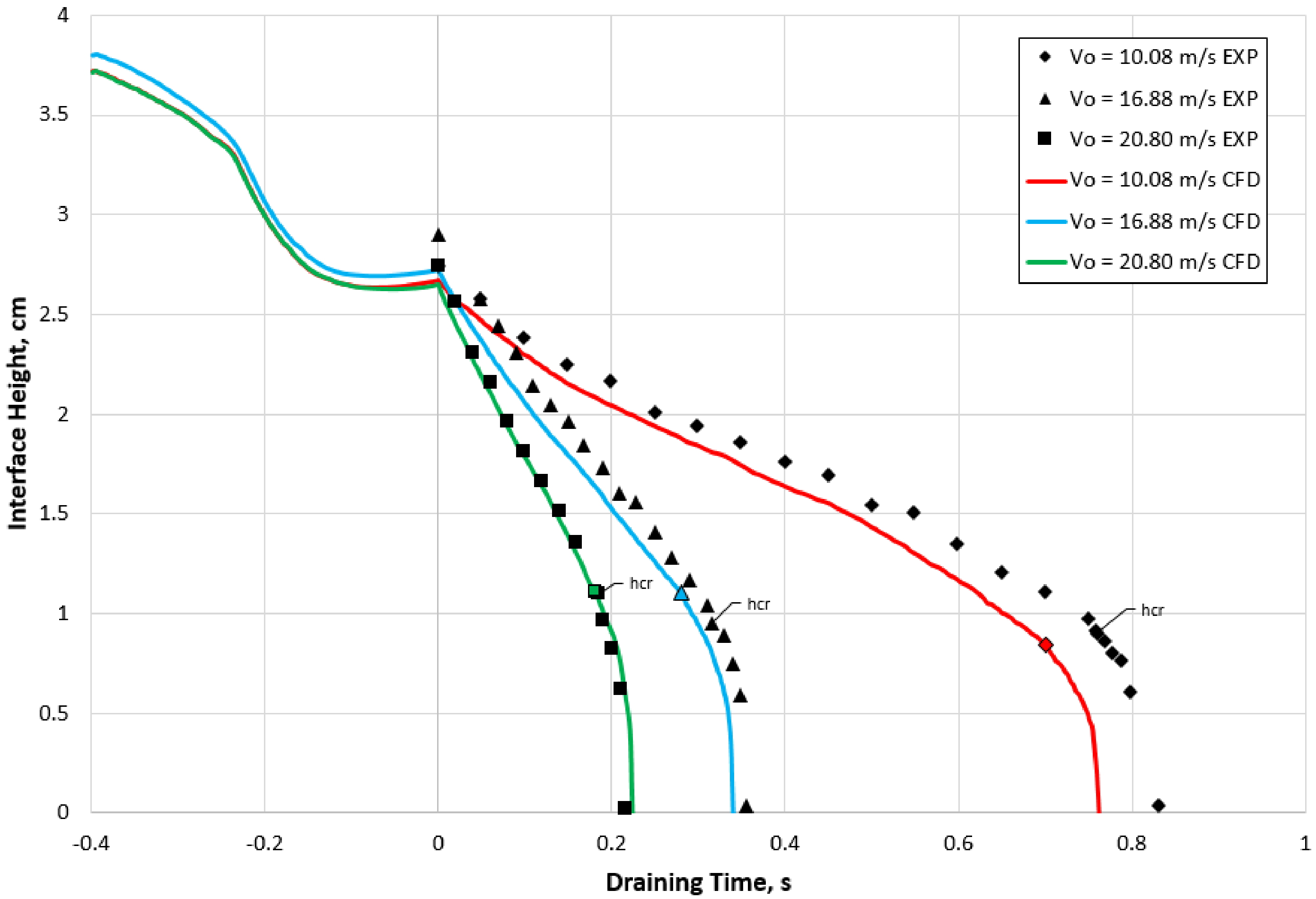
*NR=not reported

Draining Curves: Low Gravity

- Draining was initiated after 0.4 seconds of simulation time with no flow to allow centerline to reach low point while equilibrating
- Initial interface centerline heights for CFD cases are slightly lower than experiment
  - Draining initiated at different times in experiment
  - Led to slight underprediction in interface height for V_o = 16 and 20 m/s
- Interface oscillations observed in experiment

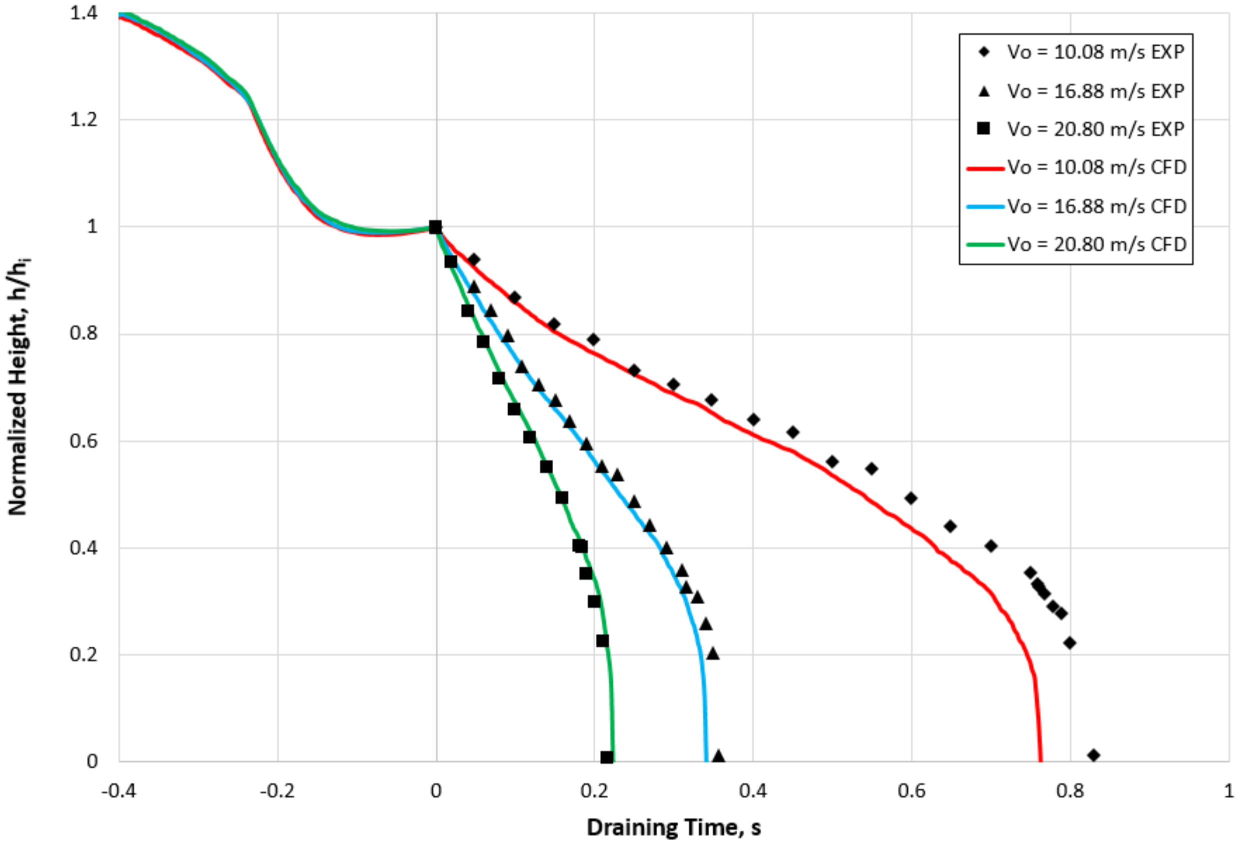
Critical Height Low-g (all heights in cm)

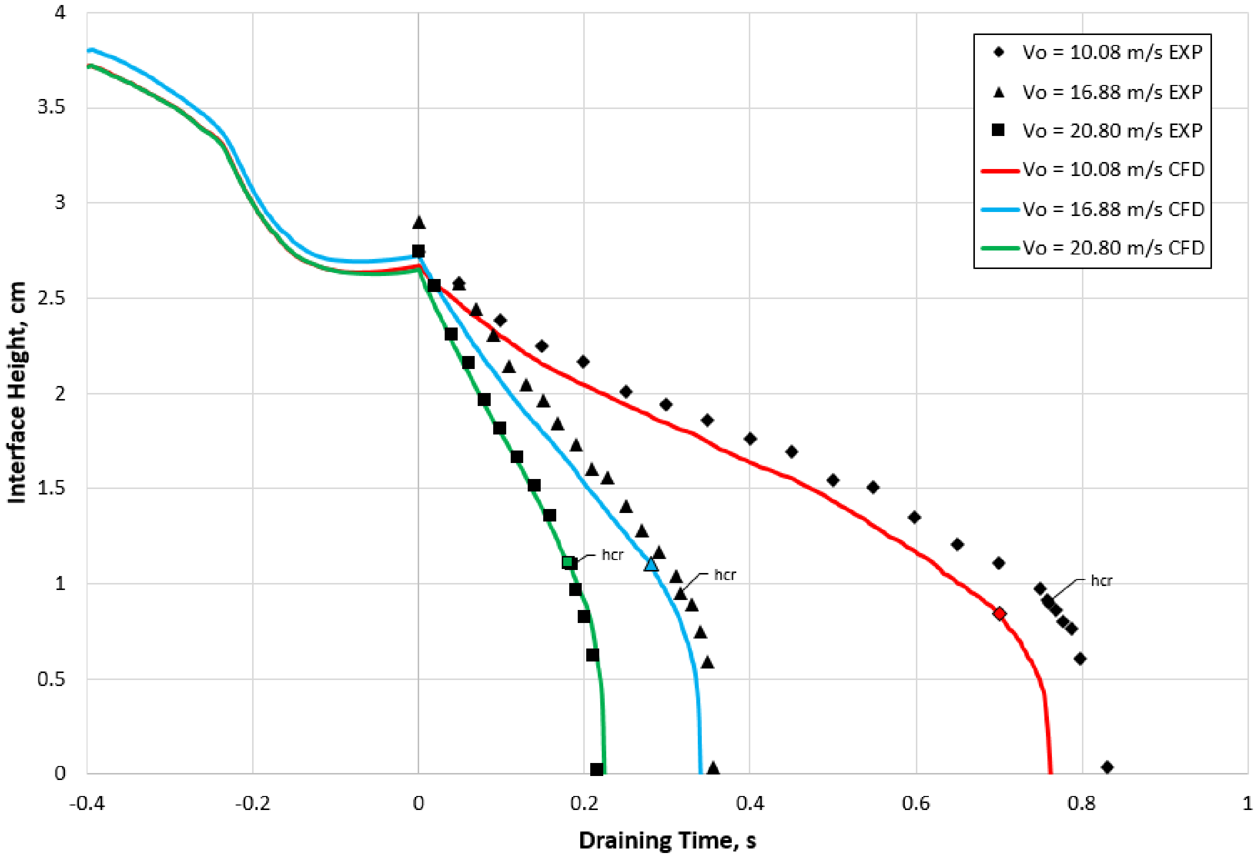
V_o, m/s	h_{cr} EXP	h_{cr} CFD	% error
2	0.75	0.78	4.0
10.08	0.90	0.84	6.0
16.88	0.95	1.11	15.9
20.80	1.10	1.11	1.1



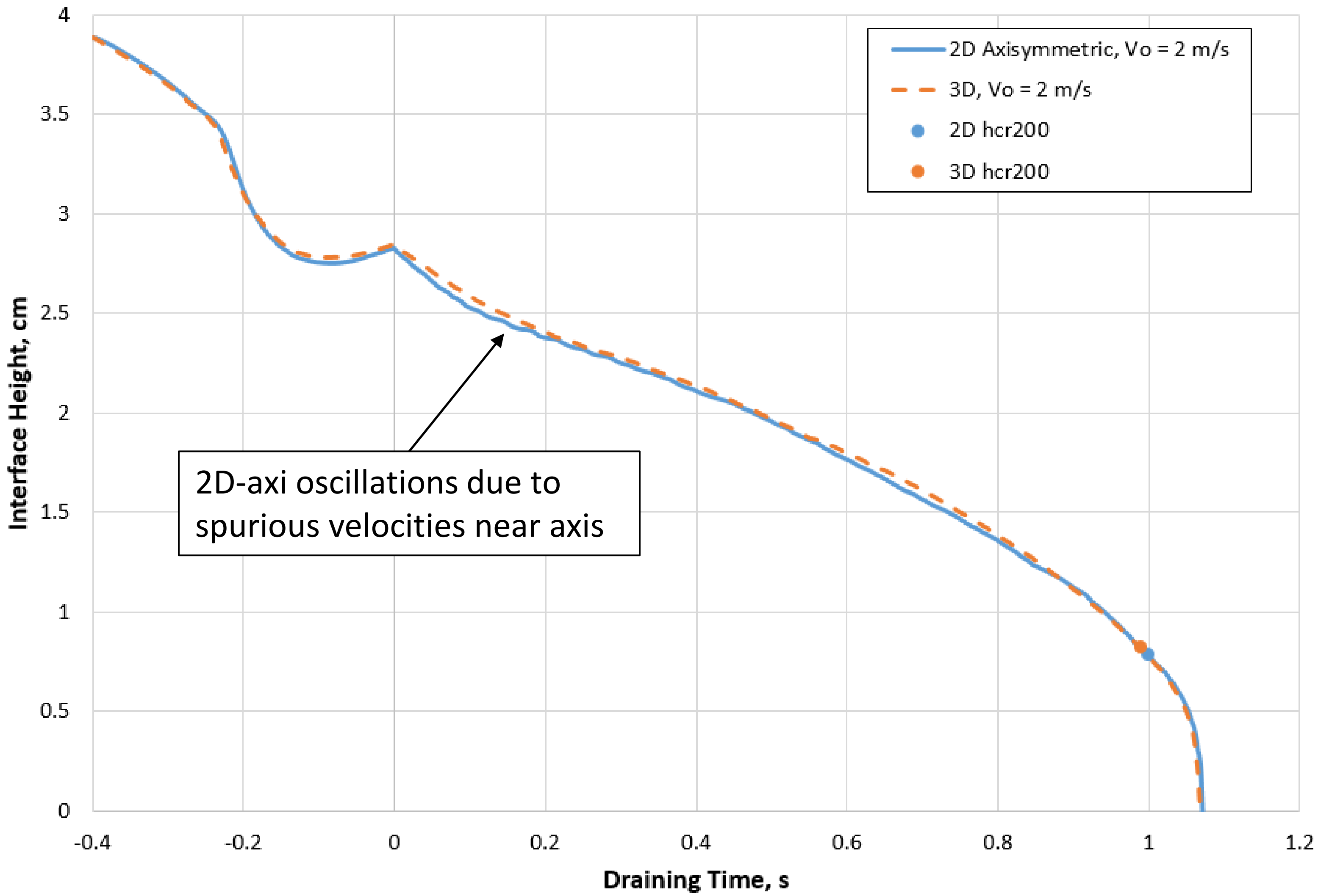
Draining Curves: Low Gravity Normalized Heights

Normalize Interface Height by h_i



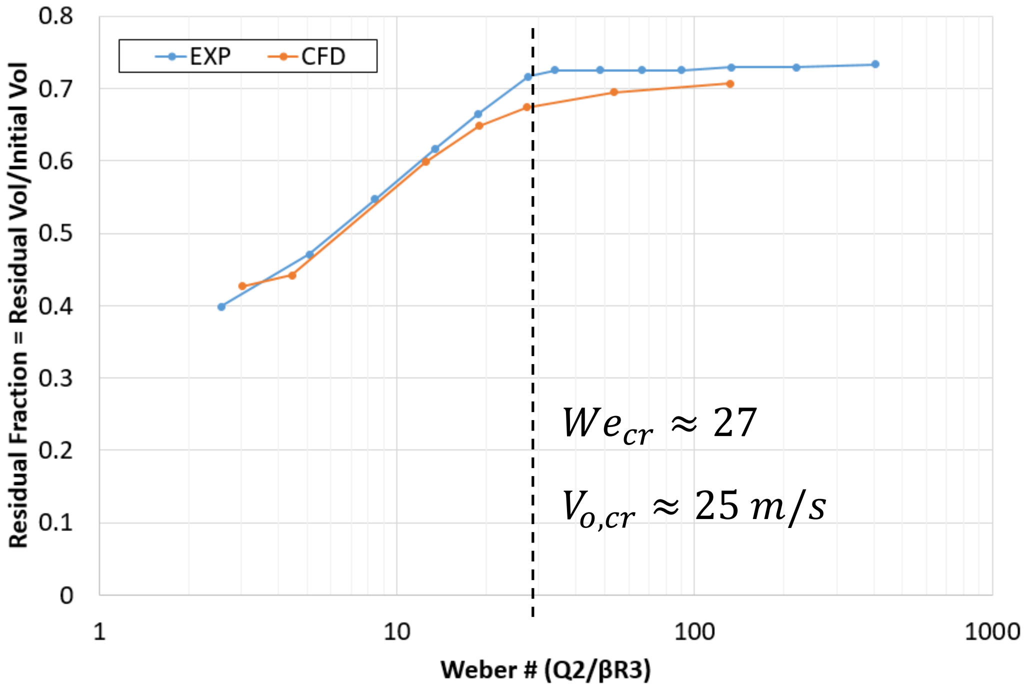


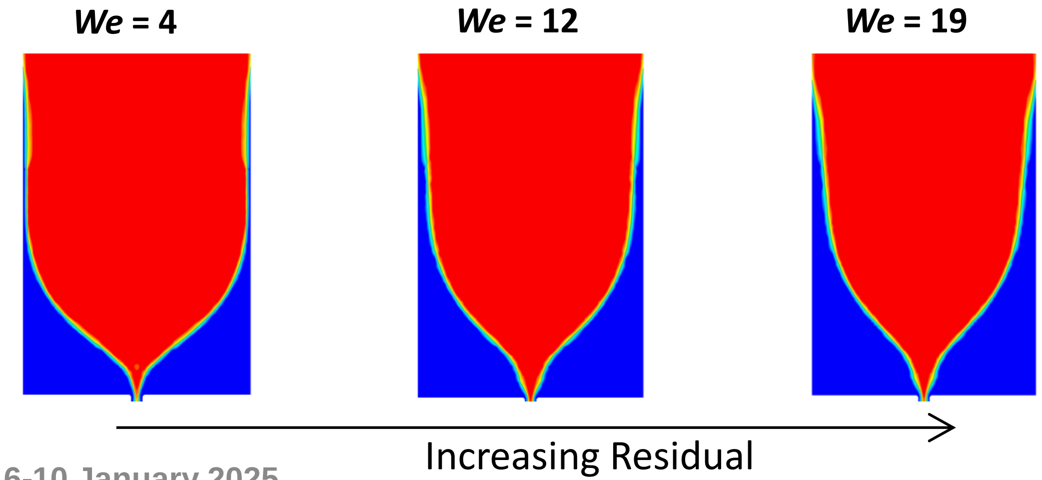
2D-Axisymmetric vs 3D Check



Liquid Residuals in Low Gravity

- Residual liquid is the untransferable propellant due to VPT
- Residual liquid increases with decreasing settling acceleration and increasing flow rate
- Abdalla and Berenyi [1] showed there exists a "critical" flow rate in which above it the residuals remain constant
- CFD predications compare reasonably well with experiment and captures asymptotic behavior
- Possible explanations for discrepancies:
  - Ref. [1] reports g-force ~10^{-5}g, current operators say 10^{-4}g to 10^{-3}g achievable
  - Vortex formation during experiment: small disturbances can lead to small turbulent eddies growing into large vortex at drain
  - Interface oscillation may reduce effective velocity above drain





Discussion and Conclusions

- Only 60% of the initial liquid is drained at the lowest outflow velocity, diminishing to 30% at high velocities
- For 1g, all outflow velocities expelled more than 60% of the initial liquid
- Microgravity can have a drastic effect on liquid residuals
- Although this experiment was set out to characterize VPT through correlations rather than reduce residuals, it highlights the need to employ methods to delay VPT to make on-orbit propellant transfer realizable
  - Increase settling acceleration
  - Reduce flow rate
  - Internal tank hardware such as vanes and baffles

- **CFD model comparisons:**
  - Qualitatively predicted liquid-vapor interface shape very well
  - h_{cr} and h_{vi} were predicted within 25%, with most predictions within 10%
  - Predicted liquid residuals within 6% and captured asymptotic trend

Future Work/Additional Studies

- Adaptive Time-Step + Adaptive Mesh Refinement
- Geometric dependence: domed-tanks, outlet configuration, baffles, etc.
- Post-VPT behavior: model two-phase flow through feedline post-VPT to determine flow rate reduction and tank pressure response
- Effect of initially swirling liquid/vortex due to in-space maneuvers on VPT/liquid residuals

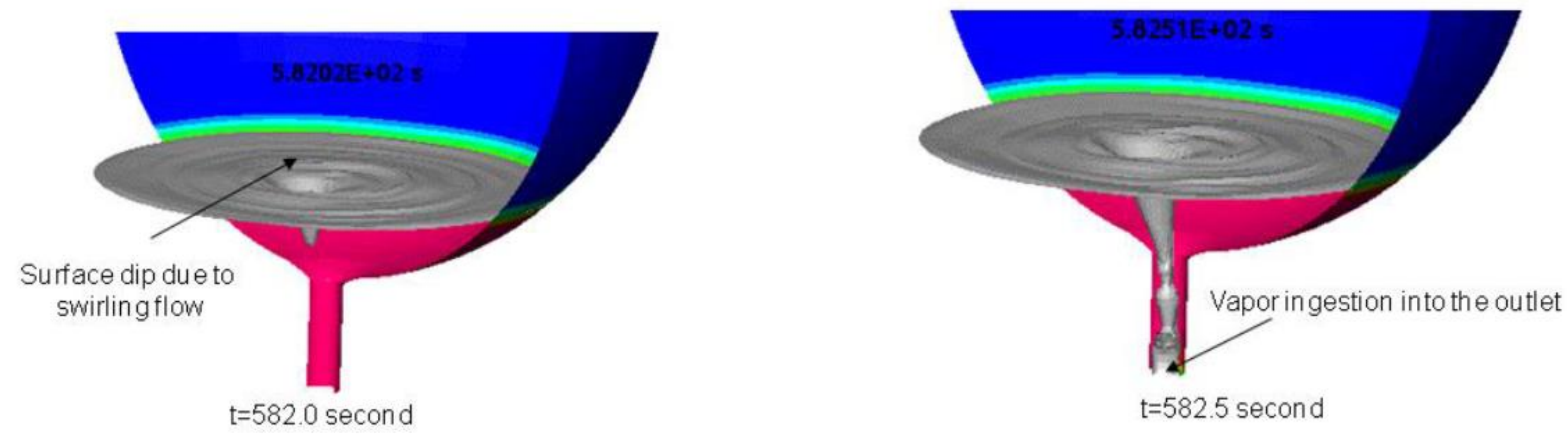


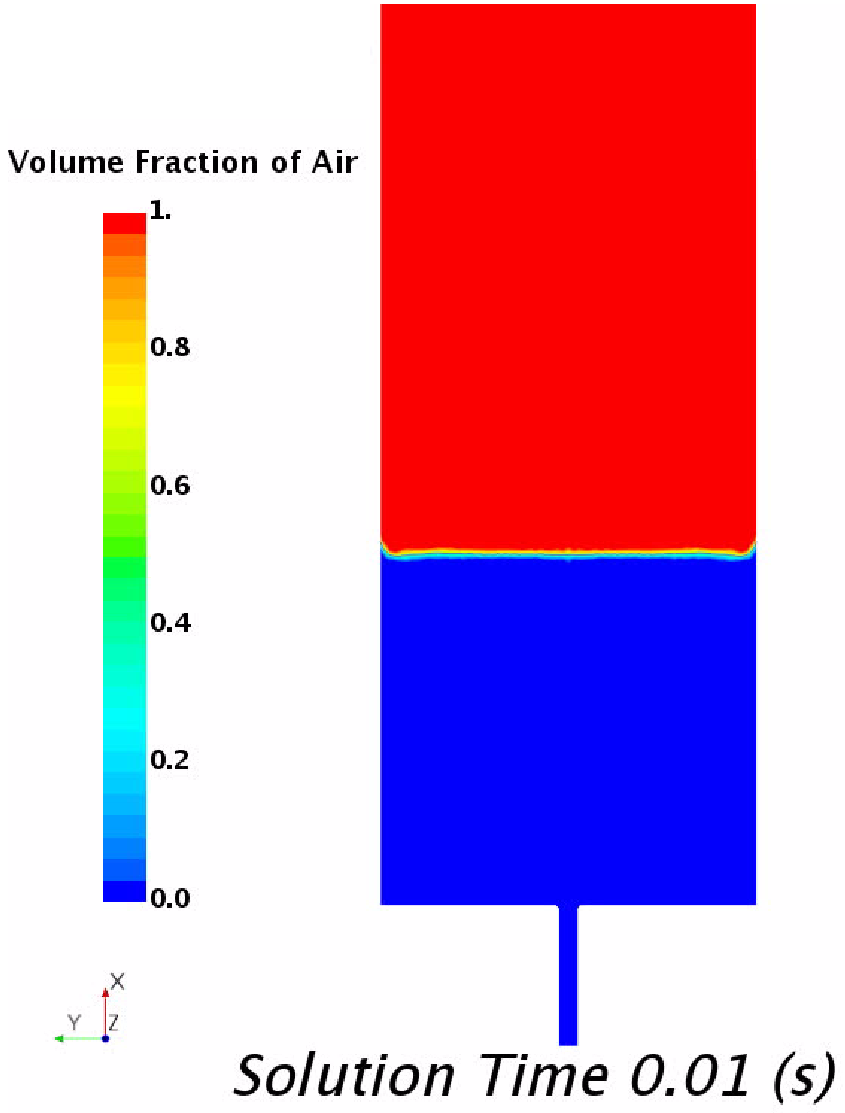
Figure 10. Formation of a dip and earlier vapor ingestion into the outlet, leading to higher residual mass

[4] Yang et al., 2017

References

1. Abdalla, K. L., Berenyi, S. G., “Vapor Ingestion Phenomenon in Weightlessness,” NASA TN D-5210, 1969.
2. Berenyi, S. G., Abdalla, K. L., “Vapor Ingestion Phenomenon in Hemispherically Bottomed Tanks in Normal and in Weightlessness,” NASA TN D-5704, 1970.
3. Brackbill J. U., Kothe, D. B., Zemach, C., “A continuum method for modeling surface tension,” J. Comp. Phys. Vol. 100, 1992, pp. 335–354.
4. Yang, H. Q., Peugeot, J. W., West, J. S., “A Computational Fluid Dynamics Study of Swirling Flow Reduction by Using Anti-Vortex Baffle,” AIAA Paper 2017-1707, Jan. 2017.

Questions?



BACKUP