

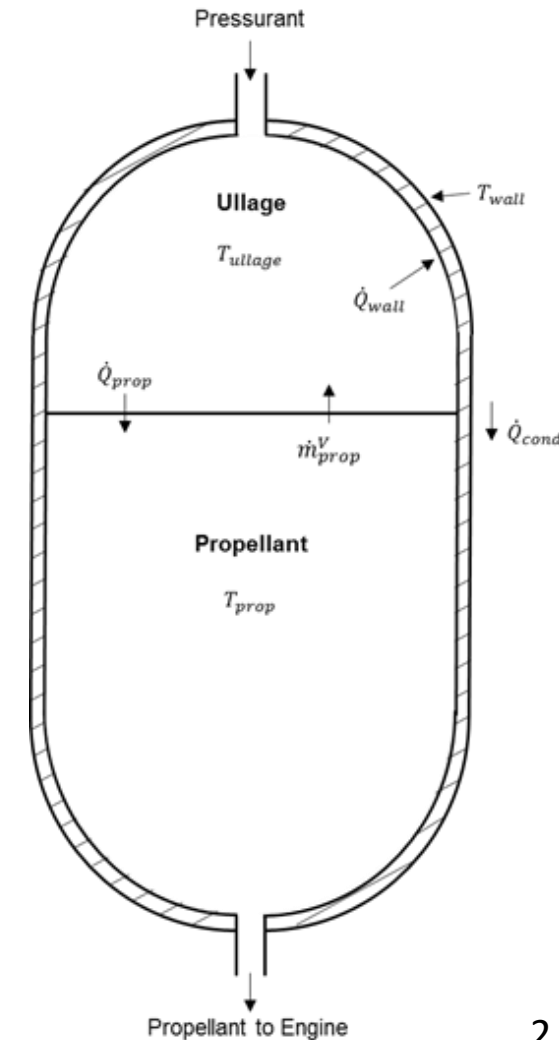
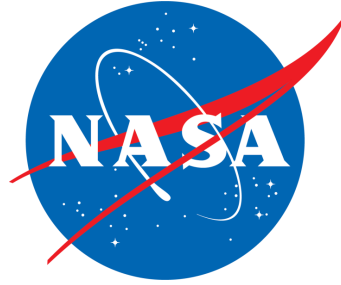


Validation of a Stratified Ullage Nodal Model Simulating Cryogenic Tank Pressurization

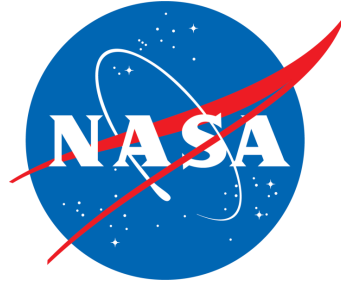
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Andre LeClair, Alok Majumdar (NASA Marshall Space Flight Center)
31st Space Cryogenics Workshop | May 13-15, 2025 | Incline Village NV

Background

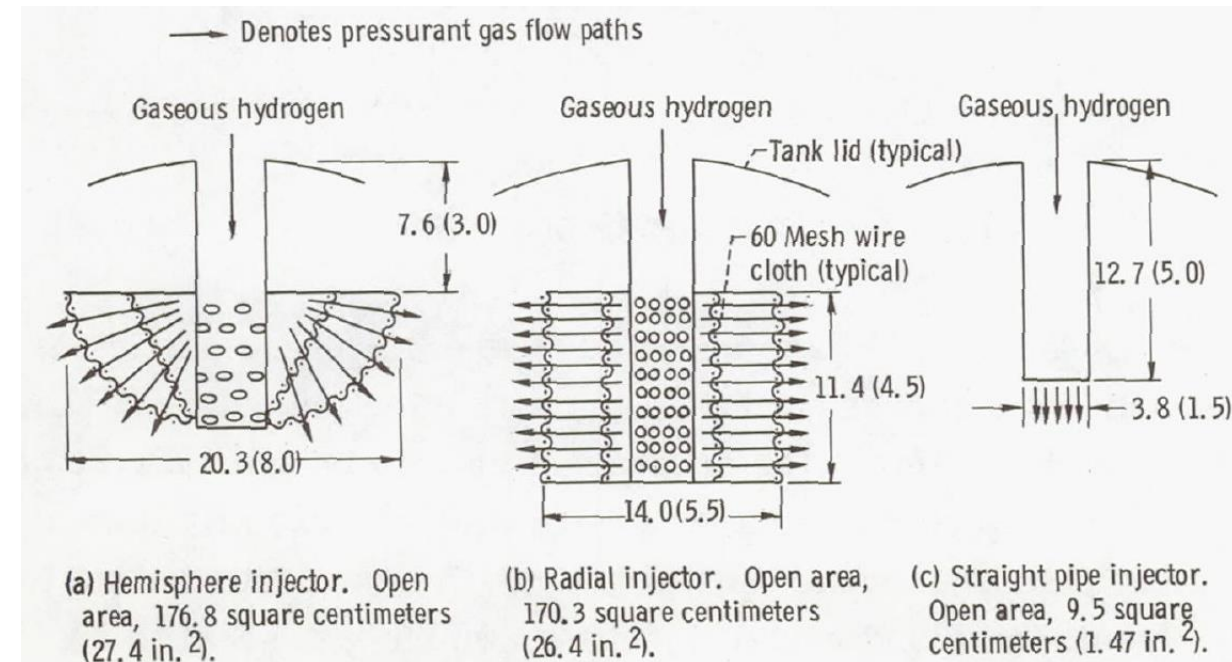
- Launch vehicle propellant tanks are pressurized with gas.
- As the tank drains, pressurant gas must be continuously added to the growing ullage volume.
- In cryogenic propellant tanks, heat transfer to the cold tank walls and liquid surface cool the ullage gas, requiring even more pressurant.
- Mass transfer through condensation and evaporation can also be significant, especially during autogenous pressurization.
- Objective of this work is to validate with experimental data thermo-fluid models that predict the amount of pressurant required to drain the tank at constant pressure.



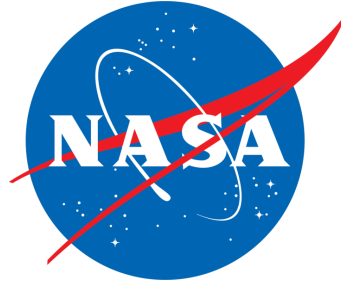
Experimental Test Configuration at the NASA/Lewis Research Center K-Site



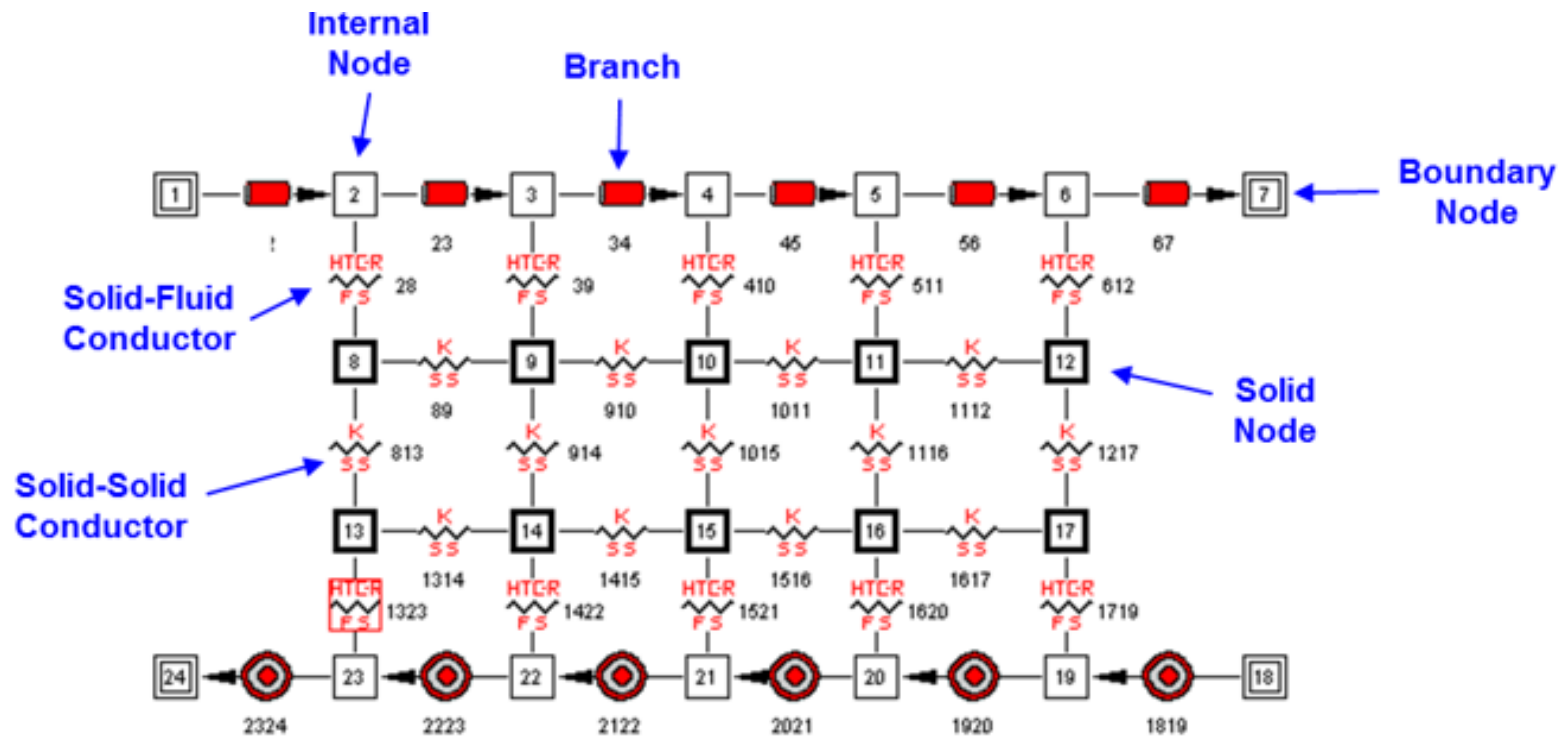
- 1.52 m (5 ft.) diameter spherical aluminum tanks with 7.62 mm (0.30 in) and 4.09 mm (0.16 in) tank wall thickness.
- Liquid hydrogen propellant drains from 95% to 5% fill level
- Gaseous hydrogen maintains 345 kPa (50 psia) tank pressure
- Hemispherical, radial, and pipe pressurant injector configurations.
- 280 K (44°F), 167 K (-159°F), and 333 K (140°F) pressurant inlet temperature.



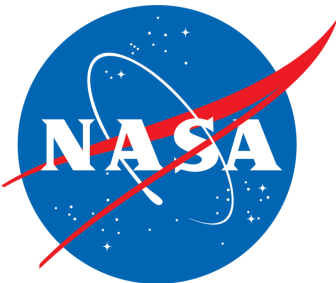
Generalized Fluid System Simulation Program (GFSSP)



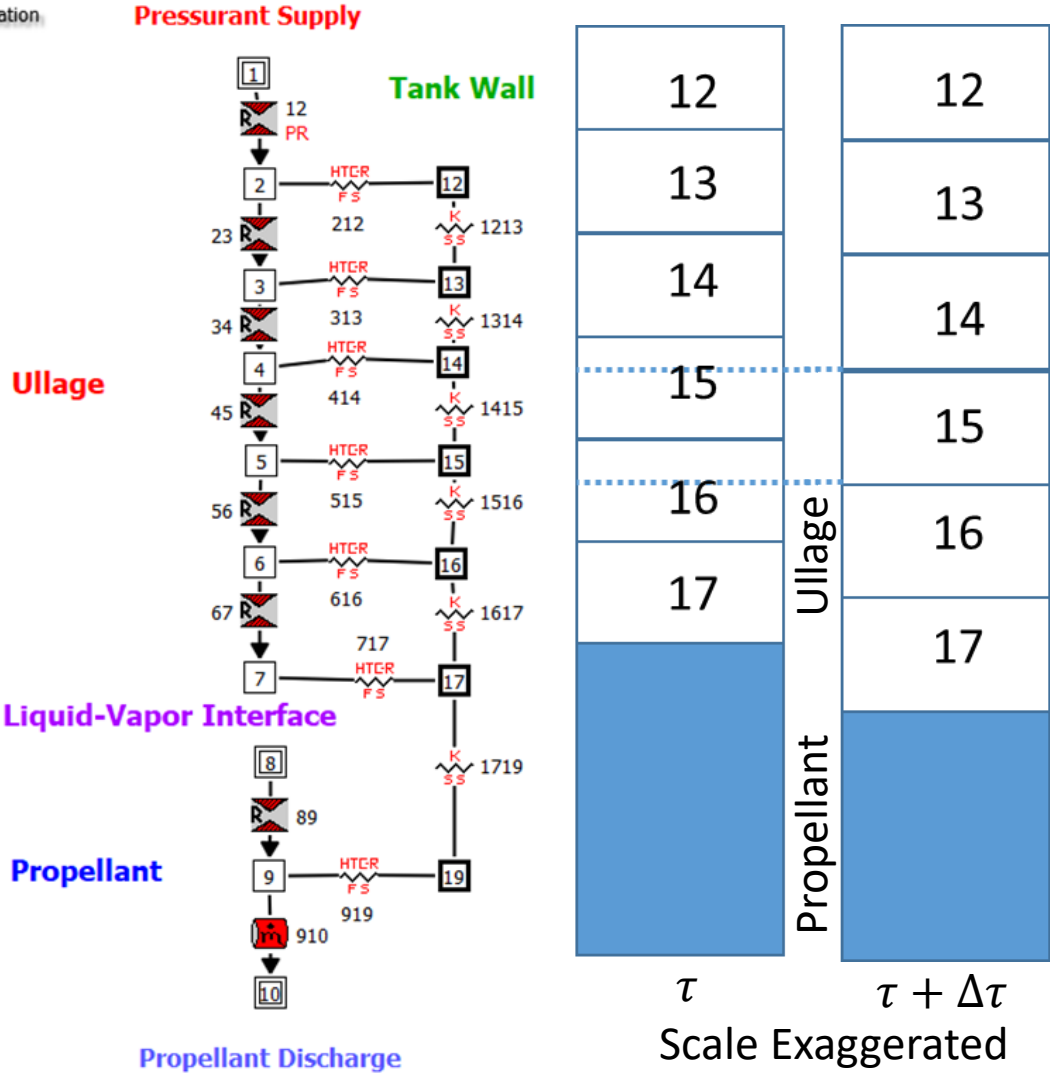
- GFSSP is a finite-volume, network-flow solver developed at NASA/MSFC.
- Conservation of mass and energy are solved in the nodes to get pressures and enthalpies.
- Momentum equation is solved in the branches to get flow rates.
- Conjugate heat transfer may be added with solid nodes to get wall temperatures.



GFSSP Stratified Ullage Nodal Model

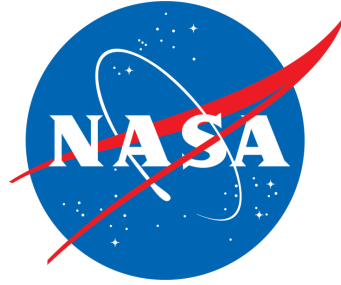


Formulation

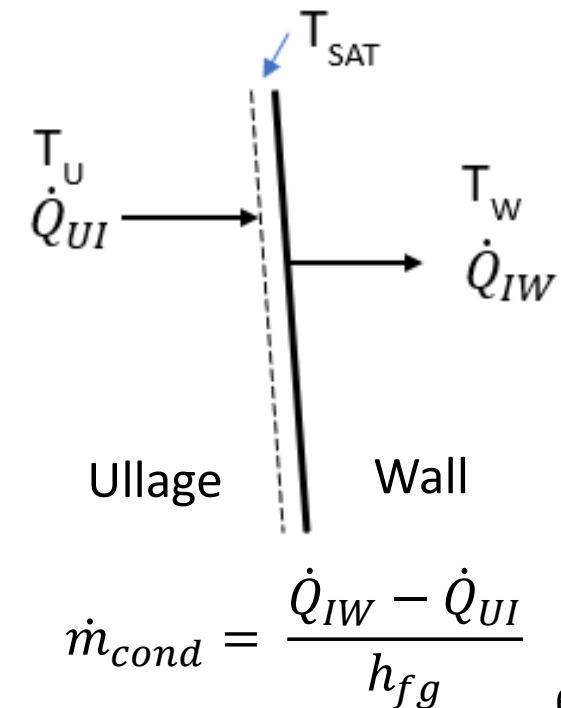


- Ullage is discretized into six layers of equal height.
- Tank wall is discretized into solid nodes with the same heights as the ullage nodes and propellant node.
- In each time step, the ullage is re-discretized into layers of equal height.
- In each time step, the tank wall solid nodes are re-discretized, and an energy balance is performed to calculate the wall temperature.

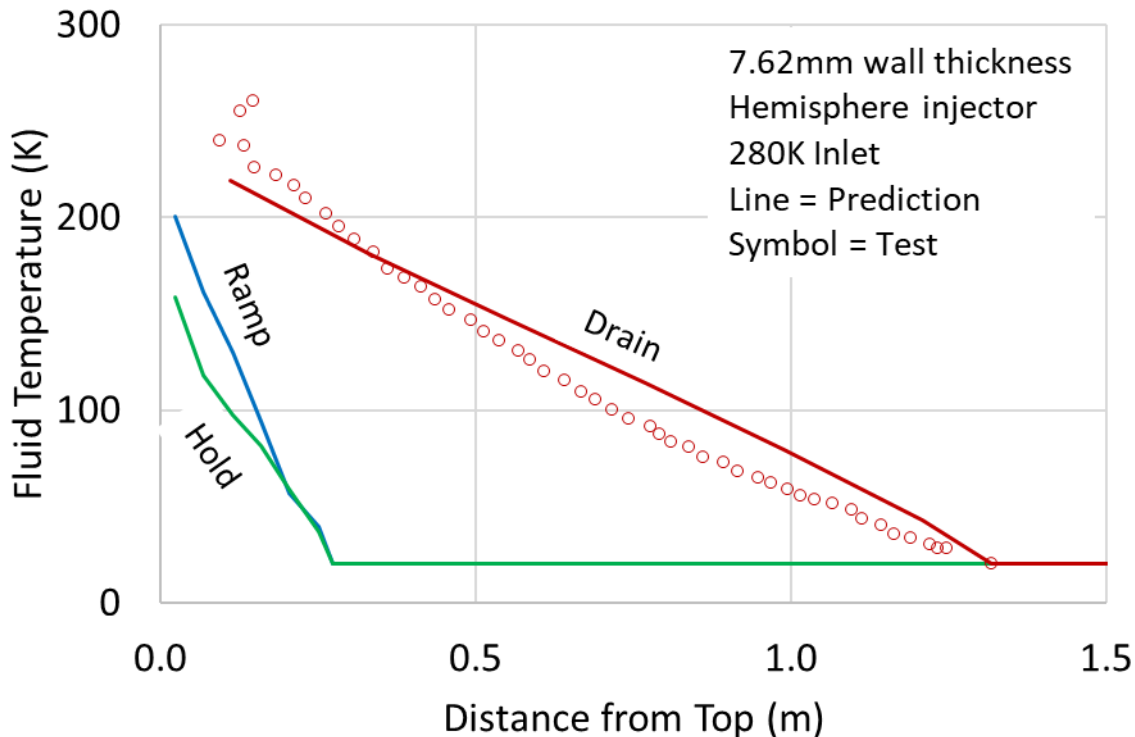
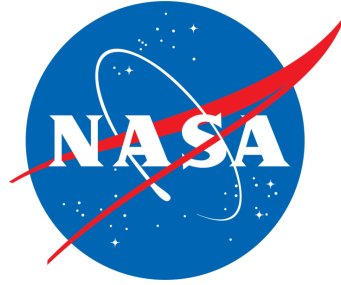
GFSSP Heat & Mass Transfer



- Single-phase heat transfer to local wall temperatures greater than saturation temperature modeled using the Woodfield mixed convection empirical correlation
- Condensation heat transfer to local wall temperatures less than saturation modeled using the Dhir-Lienhard correlation with ullage gas convection to condensate modeled using the McAdams correlation
- Condensation mass transfer modeled using the latent heat required to maintain a saturated vapor/liquid interface between ullage gas and condensate

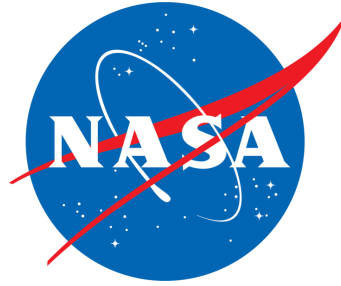


Test Timeline and Axial Ullage Temperature Profiles

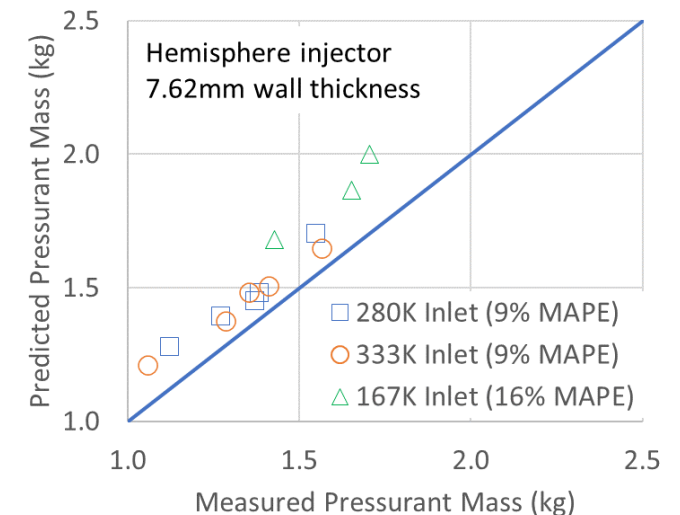
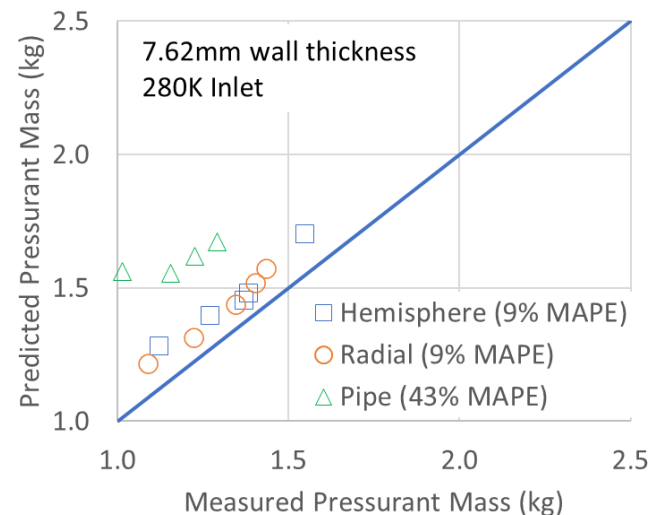
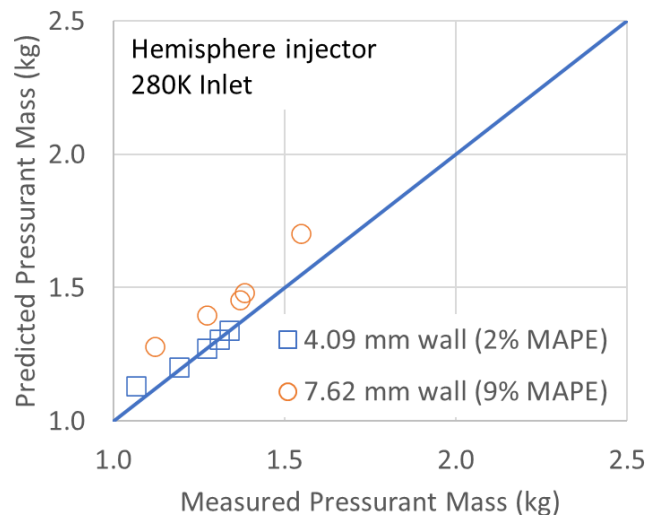


- LH2 fill at 101 kPa to 2% ullage volume
- LH2 boiloff and replenish to reach steady state at 101 kPa and 5% ullage volume
- Ramp pressure to 345 kPa in 5 to 33 seconds
- Hold pressure at 345 kPa for 20 to 30 seconds
- Drain at 345 KPa to 95% ullage volume in 132 to 532 seconds

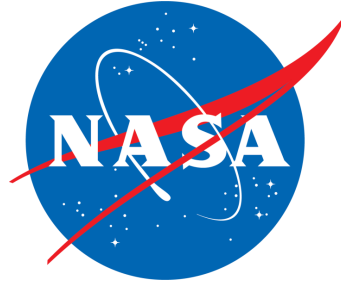
Validation of Time-integrated Pressurant Mass during drain to 95% Ullage Volume



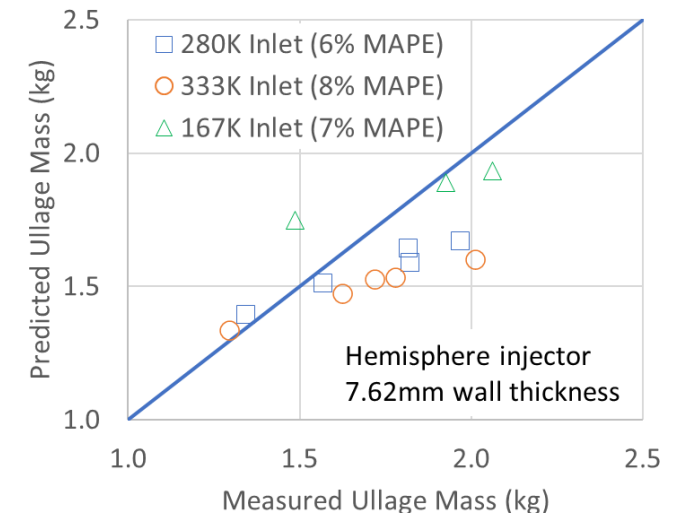
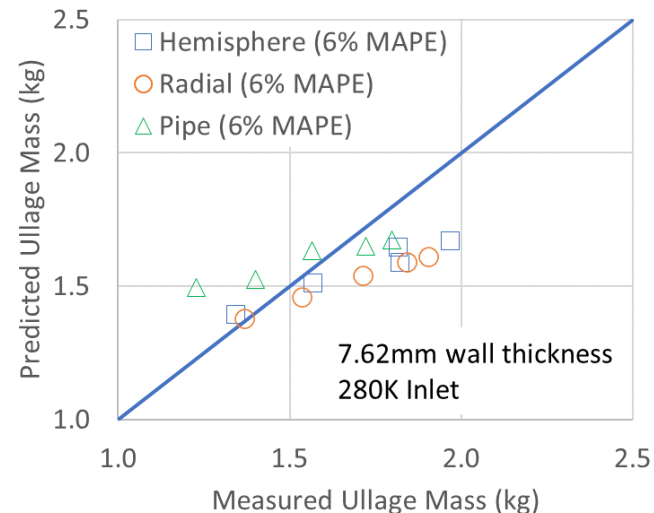
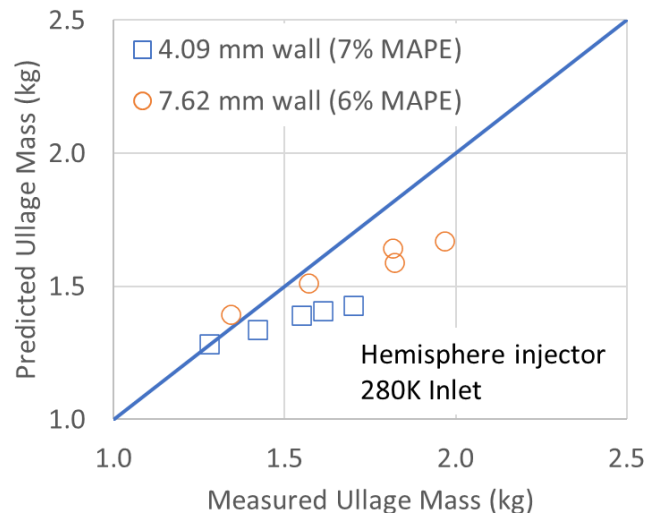
- Predicted pressurant mass during drain greater than that reported from K-Site test data with higher error observed for pipe injector, thicker tank wall, and lower inlet temperature
- Differences attributed to mixed convection correlation parameters
 - Tank height/tank diameter: Woodfield 2.8 | K-Site 0.2 to 0.9
 - Tank diameter/injector diameter: Woodfield 7.5 | K-Site hemisphere & radial 10, pipe 44



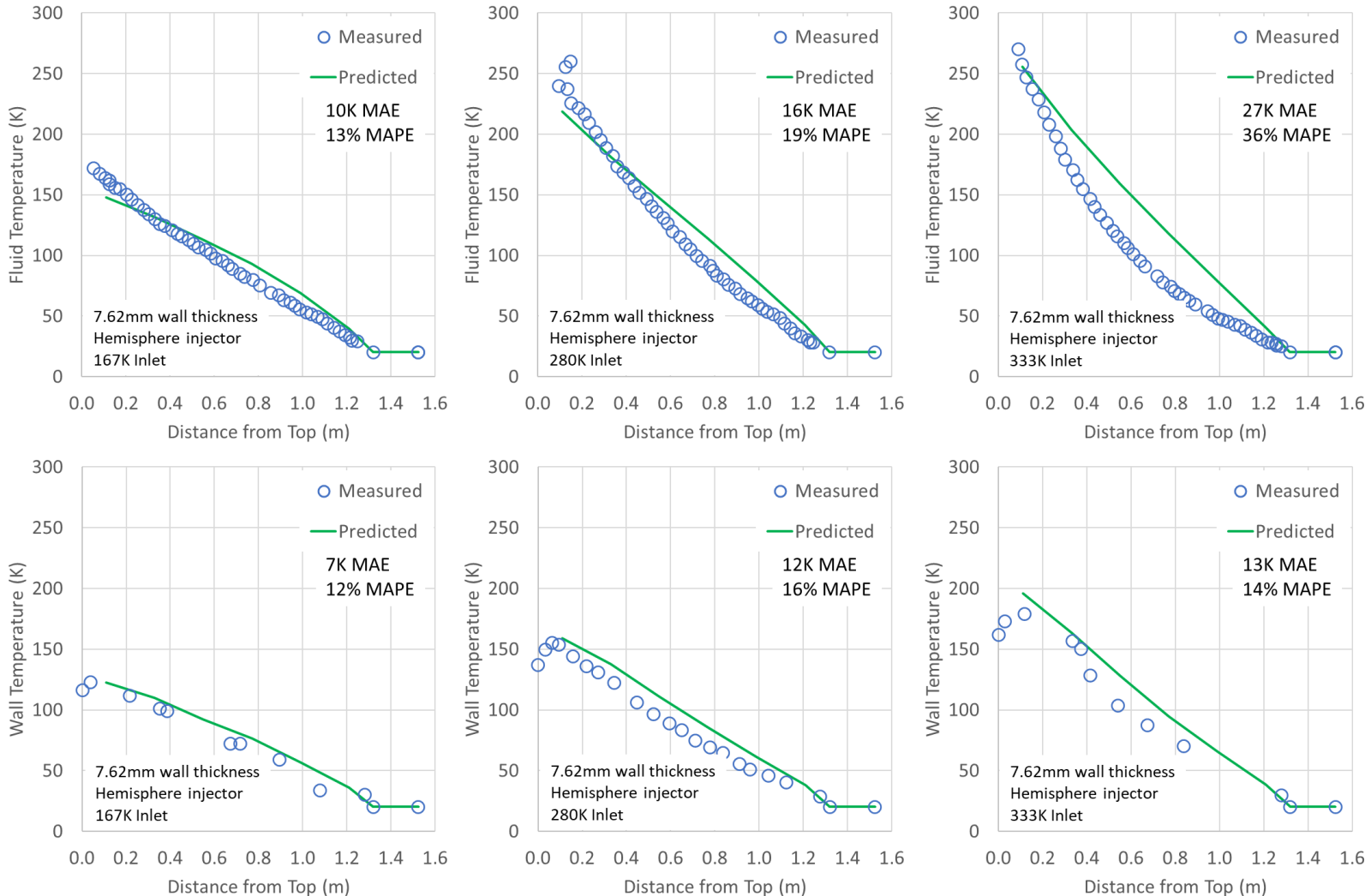
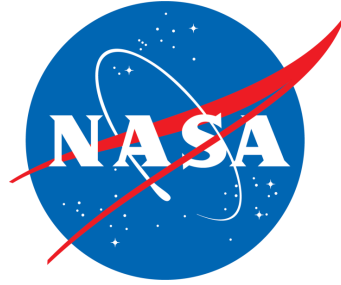
Validation of Time-integrated Ullage Mass after drain to 95% Ullage Volume



- Ullage mass after drain predicted within 8% error for all injectors, tank wall thickness, and inlet temperatures
- Differences attributed to higher fidelity test data used to calculate mass
 - Measured ullage temperatures at 339 locations resolve axial and radial profiles
 - Predicted ullage temperatures at 6 locations resolve axial profile only

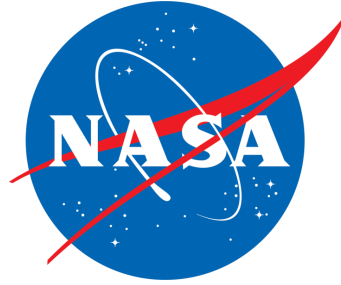


Validation of Axial Fluid and Wall Temperature Profiles after Drain: Inlet Temperature Sensitivity

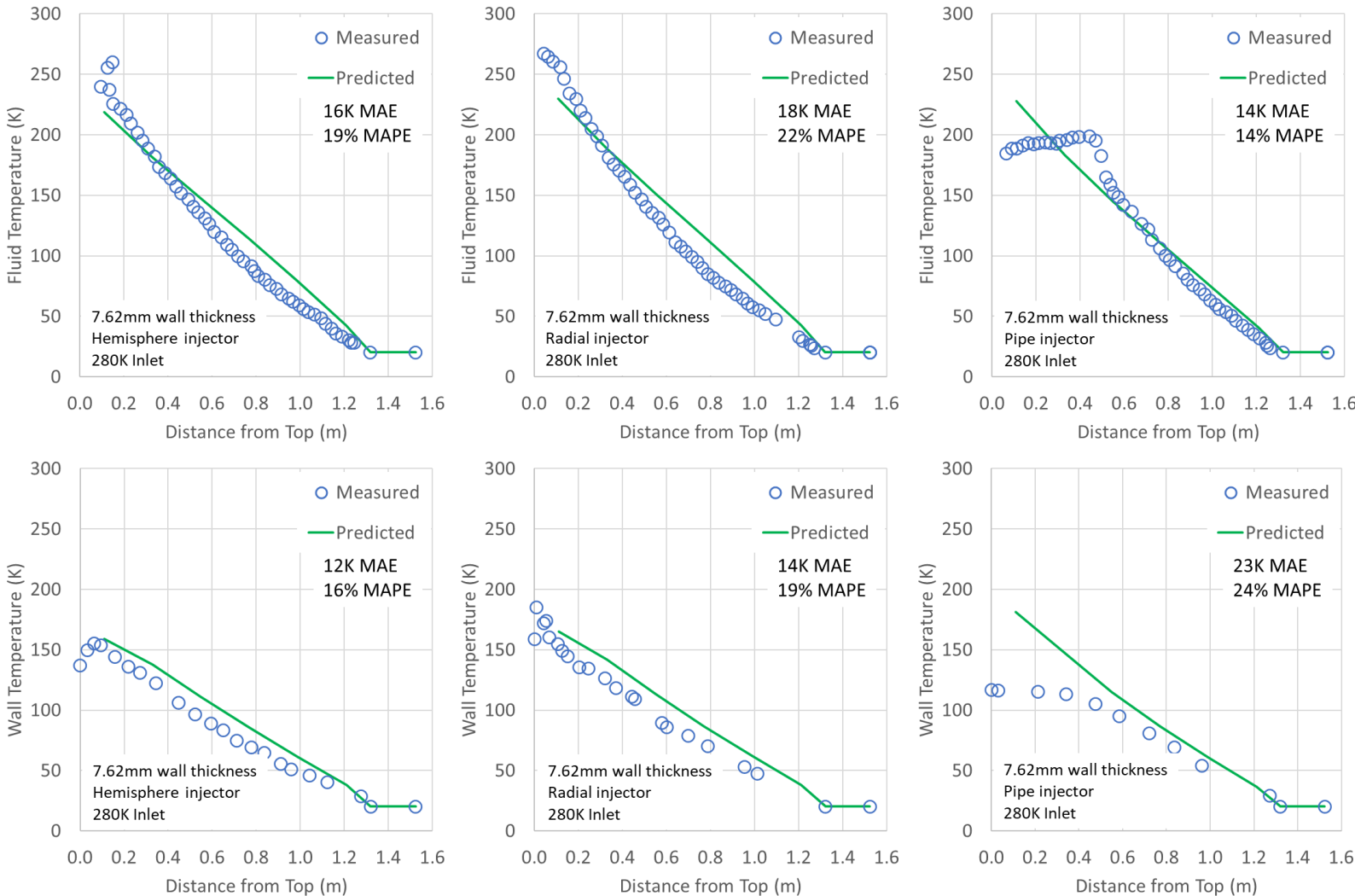


- Similar accuracy of fluid and wall temperature profiles after drain
- Greater fluid temperature error observed for 333K inlet temperature does not correspond to greater wall temperature error

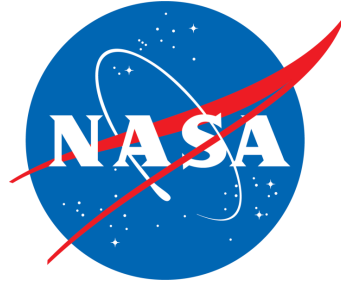
Validation of Axial Fluid and Wall Temperature Profiles after Drain: Injector Sensitivity



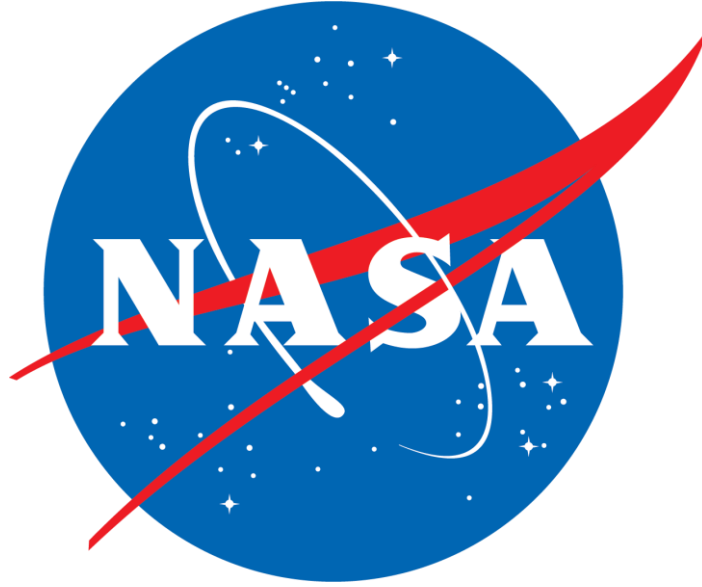
- Similar accuracy of fluid and wall temperature profiles after drain
- Pipe injector results demonstrate sensitivity to axial location that is not resolved by analysis model



Conclusions



- Stratified ullage nodal model accurately predicts pressurant mass (10% MAPE) during pressurized drain and ullage mass (8% MAPE) after drain
- Accuracy of predicted fluid ($<20K$ MAE) and wall ($<15K$ MAE) axial temperature profiles after drain is similar for hemispherical and radial injector geometries
- Pipe injector axial temperature profile demonstrates sensitivity to axial location that is not resolved by stratified ullage nodal model
 - Woodfield correlation defines average mixed convection coefficient along height of tank with axial variation reported to be less than 30% for a cylindrical tank with diameter 7.5 times injector diameter
 - K-site tank is spherical with diameter 44 times pipe injector diameter



National Aeronautics and Space Administration

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