Nodal Modeling of Helium Pressurization and Autogenous Pressurization and Draining using a Multi-Node-Ullage Approach

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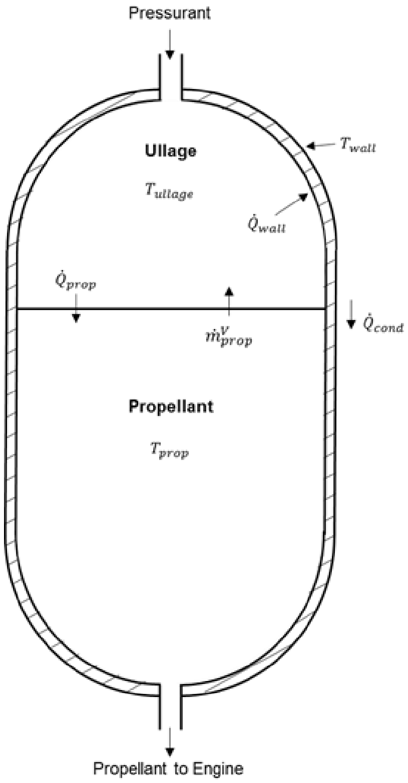
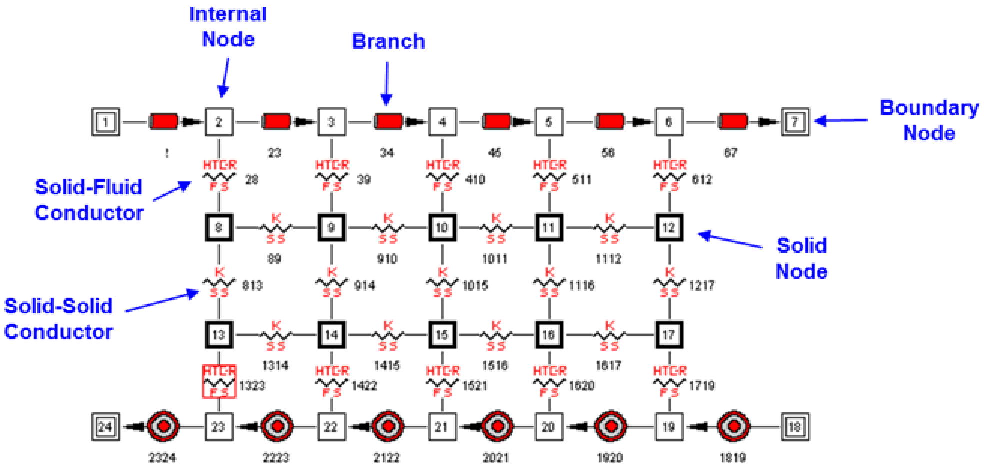
Background

- 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.
- Thermo-fluid models of tank pressurization can predict the amount of pressurant required to drain the tank and meet engine requirements.



GFSSP



- Generalized Fluid System Simulation Program (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.

Test Data

- Early-1970s tests at NASA/Lewis Research Center K-Site.
- 5-ft (1.52-m) diameter, spherical aluminum tank.
- Liquid propellant: CH_4
- Pressurants: He, CH_4, H_2, N_2
- Pressurant temperatures: 222 or 333 K
- Testing procedure:
  - 30-second press from 14.7 to 50 psia (101-340 kPa)
  - 30-second hold at 50 psia
  - 200-, 400-, or 600-second drain, maintaining 50 psia

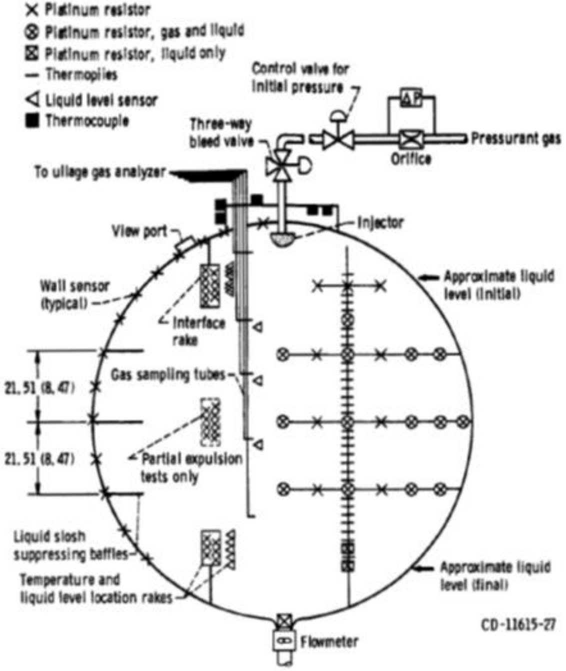
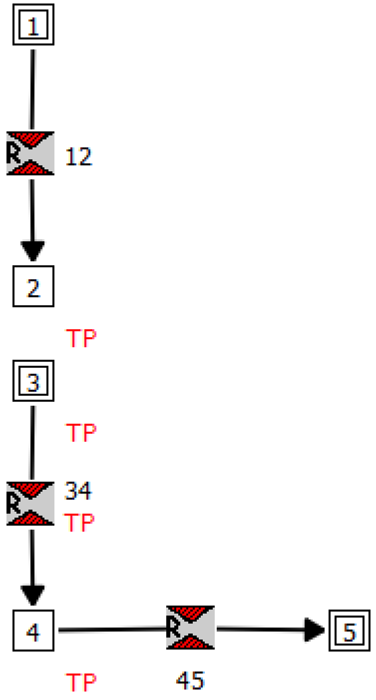


Figure 6. - Test tank instrumentation. (All dimensions are in cm (in.).)

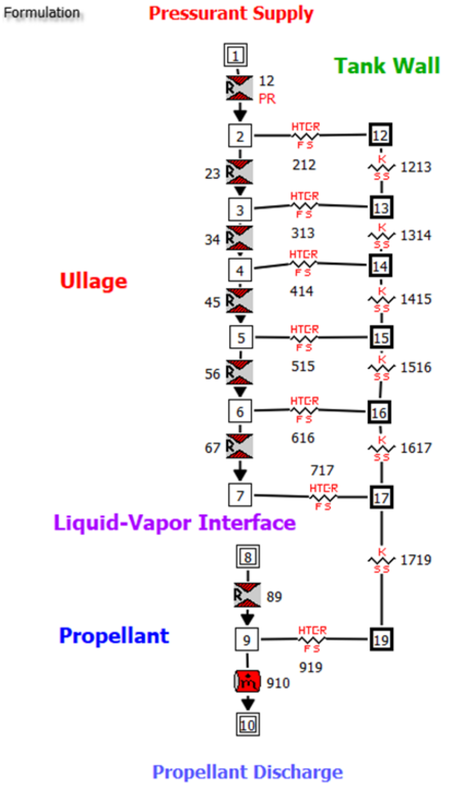
Tank Pressurization Modeling

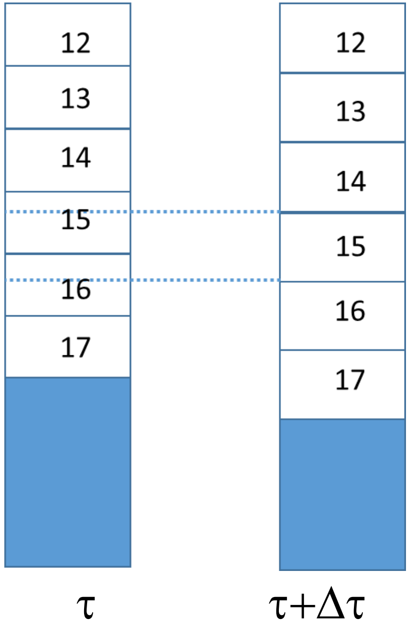
- GFSSP has a built-in tank pressurization option developed for Fastrac engine testing.
- Single-node ullage assumes that pressurant gas is homogeneous (no temperature stratification).
- Natural convection heat transfer coefficients are assumed.
- *Flores* modeled K-site tests using Helium pressurant with single-node model.
  - Predicted He consumption was 8-23% lower than experimental. Mean: -16%
- *Wendt* modeled K-site tests in Thermal Desktop with single-node ullage, 3448 node tank wall, assumed mixed convection.
  - Predicted He consumption was 2-7% higher than experimental. Mean: 4%



Multi-Node-Ullage Approach

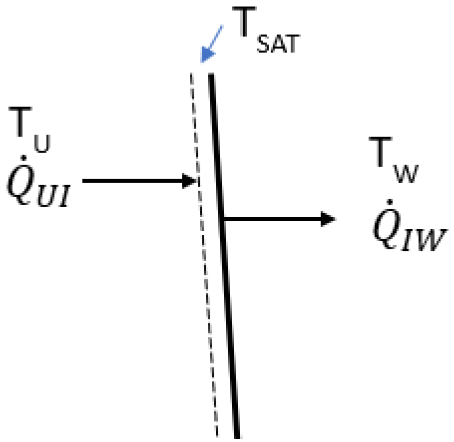
- Ullage is discretized into six layers of equal height.
- Tank wall is discretized into solid nodes with the same heights at the ullage nodes and propellant node.
- In each time step, the ullage is re-discretized into layers of equal height.
  - At the start of the run, each layer is 0.11 ft high.
  - At the end of the run, each layer is 0.64 ft high.
- In each time step, the tank wall solid nodes are re-discretized, and an energy balance is performed to calculate the wall temperature.



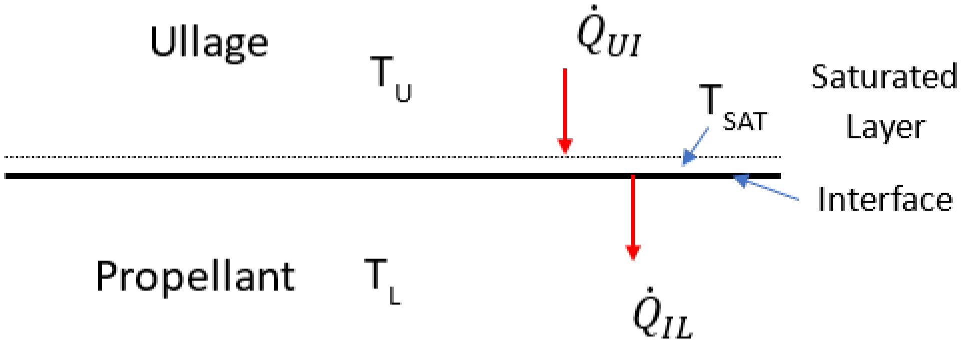


Scale exaggerated

Mass Transfer



$$\dot{m}_{cond} = \frac{\dot{Q}_{IW} - \dot{Q}_{UI}}{h_{fg}}$$

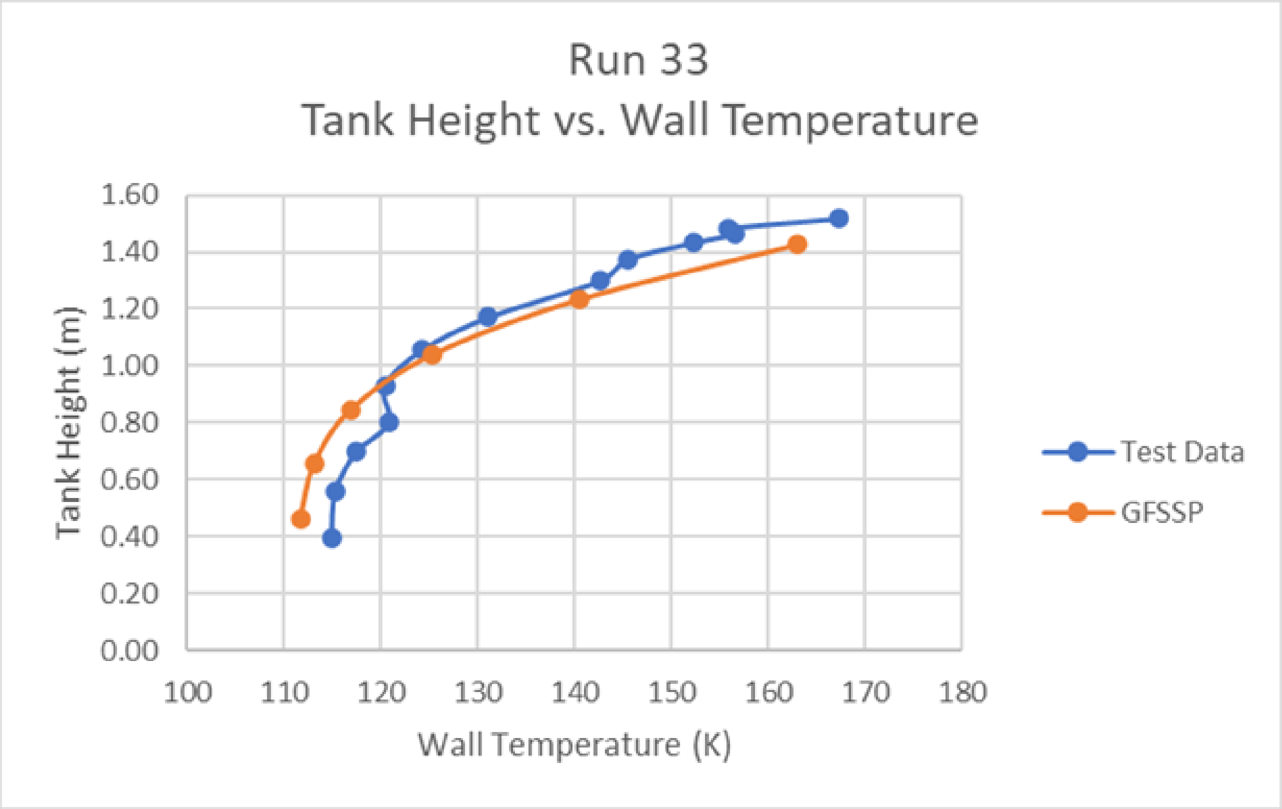


$$\dot{m}_{cond} = \frac{\dot{Q}_{IL} - \dot{Q}_{UI}}{h_{fg}}$$

Helium Consumption

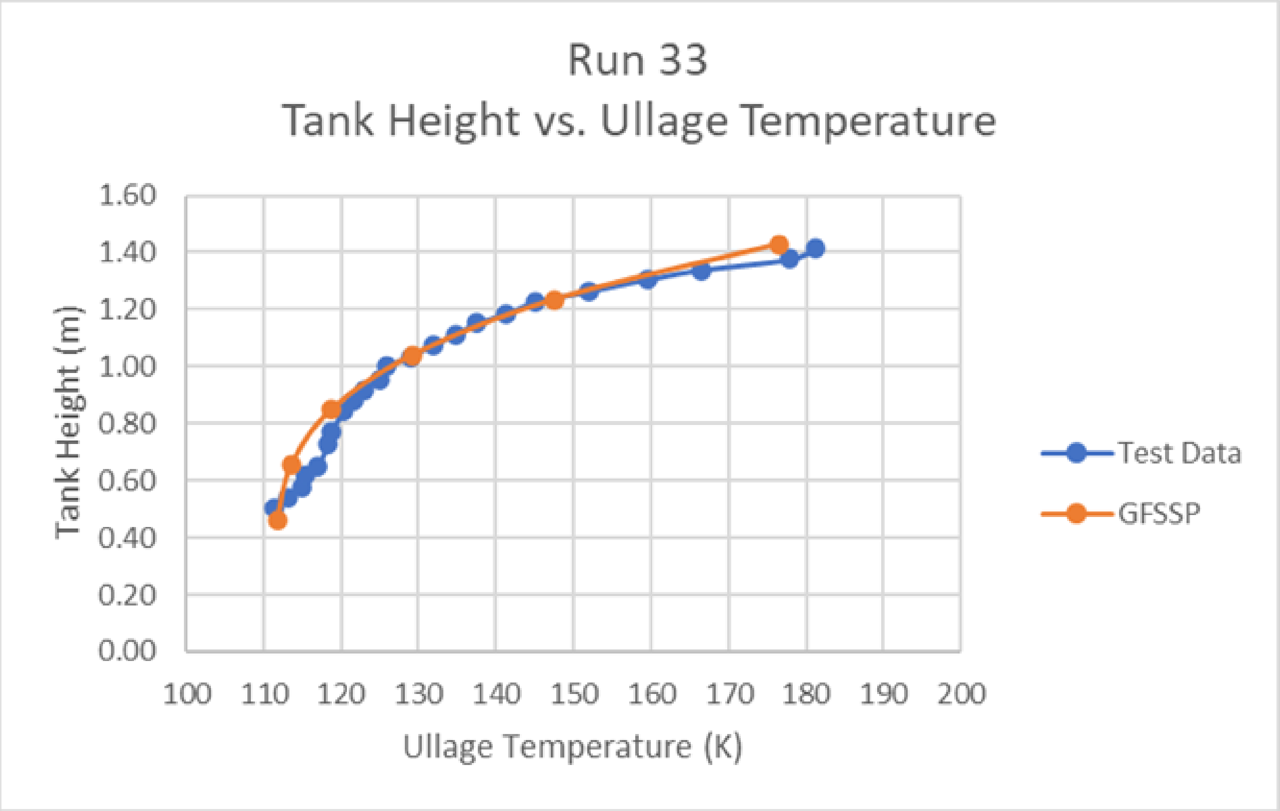
Run	He Inlet T (K)	Drain Time (s)	Measured He Mass (kg)	Natural Convection Predicted He Mass (kg)	Mixed Convection Predicted He Mass (kg)	Mixed Convection with Mass Transfer Predicted He Mass (kg)
37	229	223	1.990	1.845 (-7%)	2.080 (5%)	2.038 (2%)
36	226	389	2.096	1.936 (-8%)	2.082 (-1%)	2.029 (-3%)
33	231	622	2.145	1.974 (-8%)	2.059 (-4%)	2.002 (-7%)
42	324	224	1.895	1.674 (-12%)	1.997 (5%)	1.958 (3%)
41	331	390	2.000	1.791 (-11%)	1.994 (-0.3%)	1.944 (-3%)
40	311	599	2.091	1.868 (-11%)	1.988 (-5%)	1.932 (-8%)
Mean				**-9.5%**	**-0.1%**	**-2.7%**
MAE				**9.5%**	**3.4%**	**4.3%**

Wall Temperatures at End of Helium Press & Drain



MAE: 5K

Ullage Temperatures at End of Helium Press & Drain



MAE: 2K

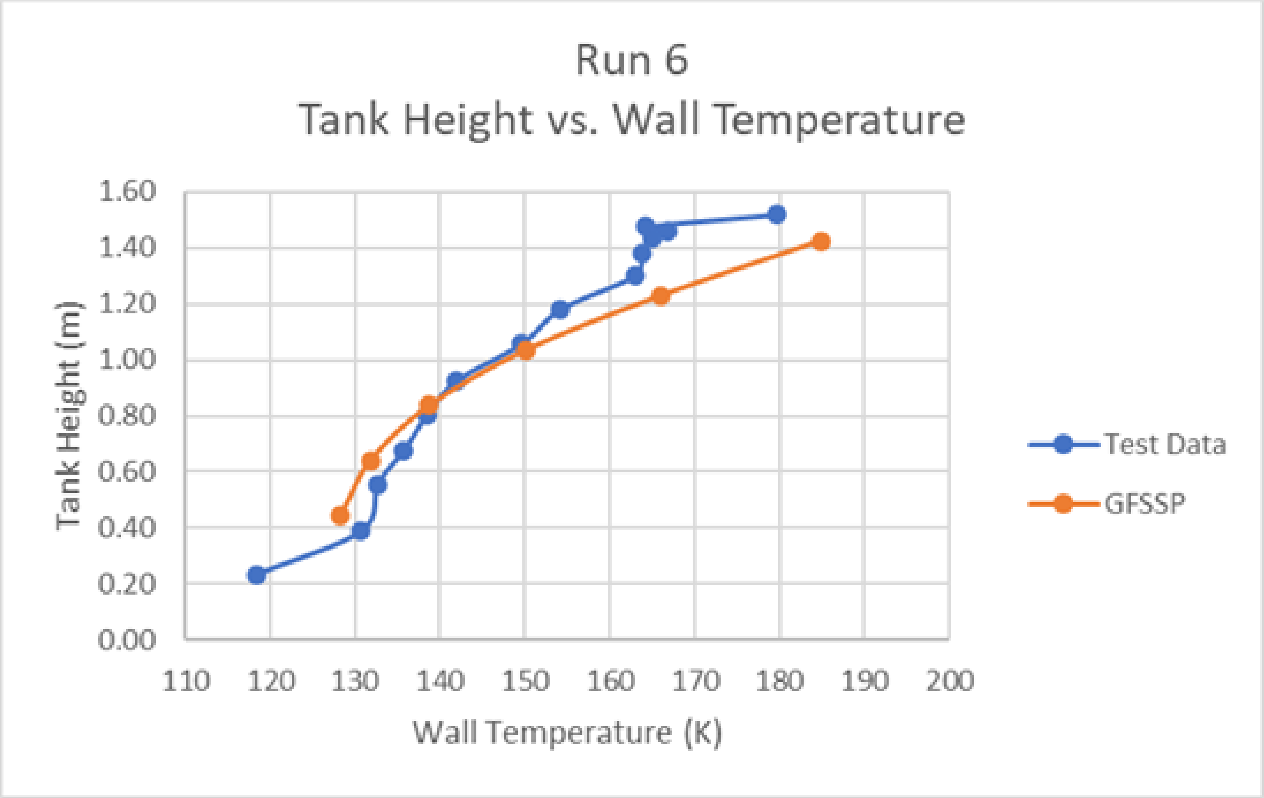
Methane Pressurant Consumption

Run	He Inlet T (K)	Drain Time (s)	Measured GCH4 Mass (kg)	Natural Convection Predicted GCH4 Mass (kg)	Mixed Convection Predicted GCH4 Mass (kg)
8	226	231	9.28	8.22 (-11%)	10.00 (8%)
7	227	405	9.94	9.18 (-8%)	11.04 (11%)
6	226	633	10.91	10.69 (-2%)	10.73 (-2%)
11	338	234	7.87	6.52 (-17%)	8.46 (7%)
10	344	410	8.71	7.66 (-12%)	9.07 (4%)
9	339	638	9.64	9.14 (-5%)	9.93 (3%)
Mean				**-9.2%**	**5.2%**
MAE				**9.2%**	**5.8%**

Methane Pressurant Condensation

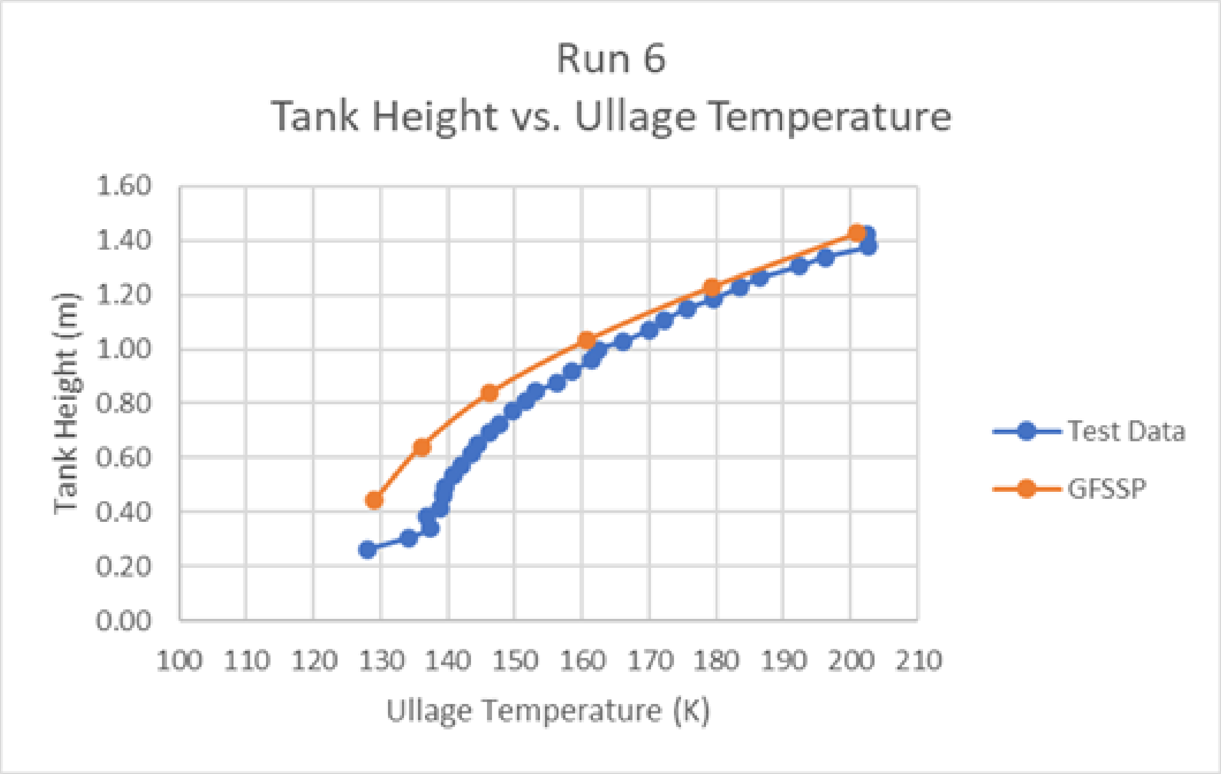
Run	He Inlet T (K)	Drain Time (s)	Measured Condensed Mass (kg)	Natural Convection Predicted Condensed Mass (kg)	Mixed Convection Predicted Condensed Mass (kg)
8	226	231	2.98	2.45 (-18%)	2.67 (-10%)
7	227	405	3.29	3.52 (8%)	3.55 (8%)
6	226	633	3.78	4.90 (30%)	3.34 (-12%)
11	338	234	2.62	2.25 (-14%)	2.58 (-2%)
10	344	410	2.95	3.20 (8%)	2.42 (-18%)
9	339	638	3.40	4.56 (34%)	3.11 (-9%)
Mean				**8.0%**	**-7.2%**
MAE				**18.7%**	**9.8%**

Wall Temperatures at End of GCH4 Press & Drain



MAE: 6K

Ullage Temperatures at End of GCH4 Press & Drain



MAE: 6K

Conclusions

- The multi-node ullage model more accurately predicts pressurant consumption than GFSSP's existing single-node ullage model.
- A mixed convection correlation more accurately predicts pressurant consumption than a natural convection correlation.
- The stratification of ullage and tank wall temperatures is predicted, with MAPE of temperatures less than 10%.
- Methane condensation and evaporation had only a small effect in the helium pressurization.
- Methane condensation must be included in autogenous pressurization. Error in the predicted condensed mass can be large (up to 34%), owing to uncertainty in the convection coefficients.
- Models typically run in 1-3 minutes.

Questions

Questions?

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