

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

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Pressurized expulsion tests of liquid methane were modeled by a nodal code using a multi-node ullage approach. Generalized Fluid System Simulation Program (GFSSP), a finite volume based nodal code was used to model the expulsion of liquid methane from a 1.52-meter (5 ft) diameter spherical tank by pressurizing with helium and gaseous methane. The purpose of the model was to estimate the amount of pressurant required and amount of condensation and evaporation of methane during the operation. The ullage was discretized into multiple nodes and each fluid node was connected to solid nodes. Both the fluid and solid nodes grow as the tank drains. The heat and mass transfer between fluid and solid node in the tank ullage was computed. The heat and mass transfer between the bottom ullage node and the liquid methane was also computed. The model predictions were compared with data from twelve test cases. The predicted pressurant consumption for helium pressurization compares with test data with a Mean Absolute Percent Error (MAPE) of 3 %. For autogenous pressurization, where gaseous methane was used to pressurize liquid methane, the predicted pressurant consumption compares with a MAPE of 6%.

I. Nomenclature

E	=	Energy (kJ/kg) of solid node as function of absolute temperature
$GFSSP$	=	Generalized Fluid System Simulation Program
MAE	=	Mean Absolute Error
$MAPE$	=	Mean Absolute Percent Error
τ	=	Time (sec)

II. Introduction

The purpose of the pressurization system in liquid rocket propulsion is to control the pressure in the gas space of the propellant tank (known as the ullage space) and the propellant mass flowrate to the engine. A mathematical model is required to predict the amount of pressurant necessary to ensure that pressure and temperature levels inside the tank remain within acceptable limits and that the propellant pressure leaving the tank satisfies the net positive suction pressure requirement of the pump feeding the engine.

Nodal codes typically model tank pressurization and draining using a single node to represent the ullage and a single node to represent the propellant. As the tank drains, the ullage node grows, and the propellant node shrinks. The heat transfer between ullage to wall and ullage to propellant is governed by natural convection [1]. Designers of liquid propulsion systems often use empirical correlations [2] to estimate the “Collapse Factor” which represents the ratio of pressurant required with heat transfer to the amount of pressurant required without heat transfer. A single node ullage model [3] of tank pressurization was developed using GFSSP (Generalized Fluid System Simulation Program) to compute the collapse factor reasonably well and later was used to model tank pressurization during test firing of the Fastrac rocket engine. The predicted tank pressure compared well [4] with the test data.

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In the early 1970's, pressurization and drain tests with liquid methane [5] were performed at NASA Lewis Research Center in a vacuum chamber. A 1.52 m (5 ft) diameter spherical aluminum tank (Figure 1) was tested to drain from 95% to 5% full using gaseous helium, hydrogen, nitrogen, and methane as pressurants. Tests were conducted with different pressurant inlet temperatures and different drain times. Measured data include the required amount of pressurant, amount of methane condensed or evaporated, and ullage and wall temperatures at various heights in the ullage space at the end of draining.

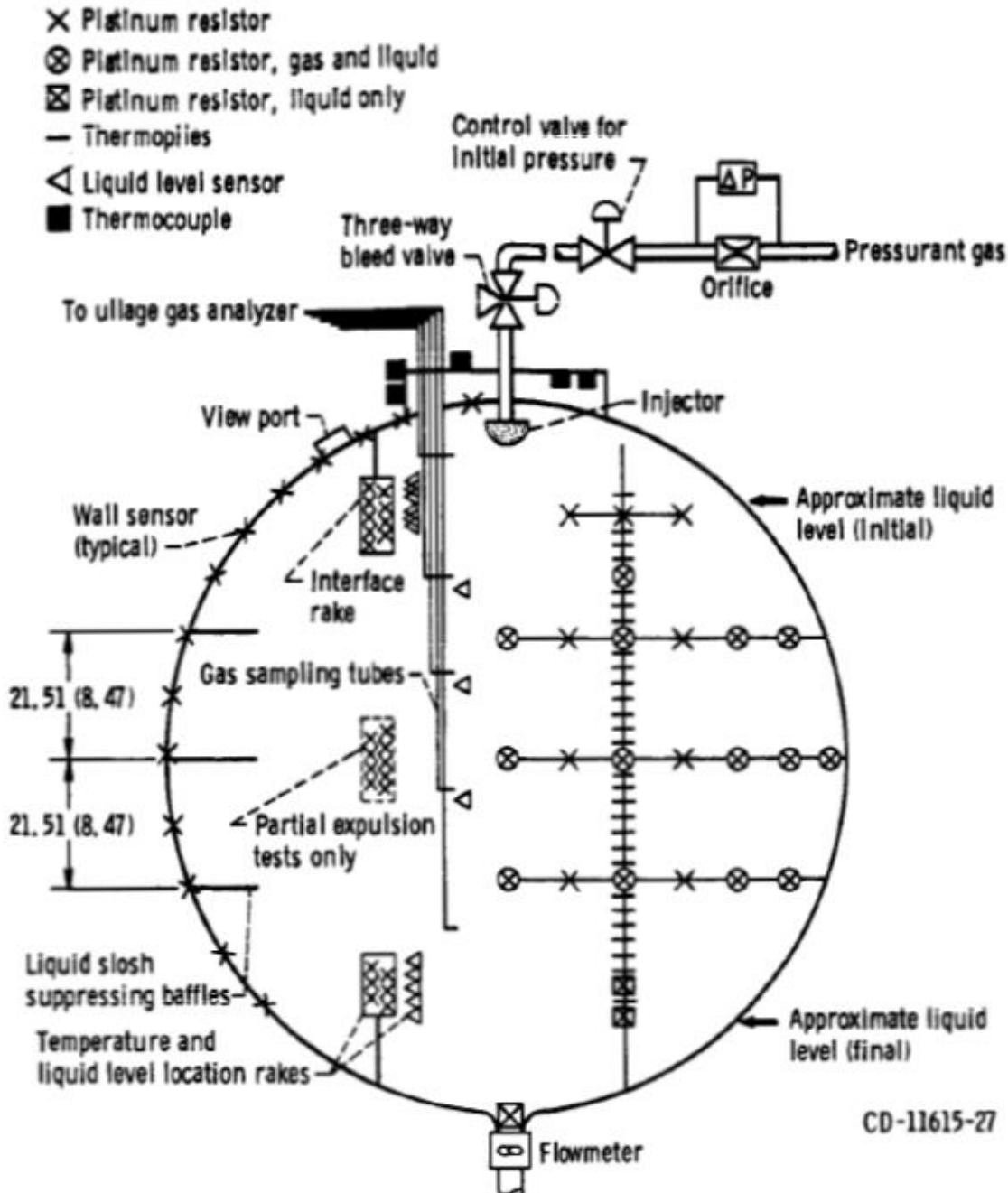


Fig. 1 K-Site Test tank and its instrumentation, dimensions in cm (in.)

A single node GFSSP [6] model was developed [7] to simulate helium pressurization and draining of the methane tank. Predicted helium consumption was 8-23% less than measured. The mean error of the six test cases was -16%.

A model with a single ullage node and 3448 fixed-geometry solid nodes was developed using Thermal Desktop [8]. This model covered the draining portion of the tests only (no pre-pressurization or hold period). Helium consumption was over-predicted by 2-7%; the mean error of the six test cases was 4%. Predicted methane evaporation during helium pressurization was an order of magnitude smaller than the measured values, which is consistent with the over-prediction of required helium pressurant. Methane consumption during autogenous pressurization was under-predicted by 3-15%; the mean error of the six test cases was -8%. Methane condensation during autogenous pressurization was also under-predicted by an order of magnitude, consistent with the under-prediction of required methane pressurant.

This paper describes the development of a GFSSP multi-node ullage model of the test configuration and compares with experimental data the predicted pressurant consumption and condensation and evaporation of methane for both helium and autogenous pressurization using gaseous methane.

III. Test Data

This section briefly reviews the equipment and procedures of the pressurization and draining tests reported in [5]. The test tank was a 1.52 m (5 ft) diameter aluminum sphere, with average wall thickness of 0.762 cm (0.30 in). The tank was mounted inside a vacuum chamber to minimize heat leak from the ambient. As shown in Figure 1, measured flow rates of pressurant gas could be added at the top of the tank. Liquid drains from the bottom of the tank at measured flow rates. Rakes inside the tank provide measurements of temperature and liquid level as functions of height. Sampling tubes at five heights permit the determination of the relative concentrations of different gas species in the ullage. External wall sensors provide wall temperature measurements at different heights.

Although the tests conducted included runs with sloshing, pressurants such as hydrogen and nitrogen, and partial expulsions to the 50% fill level, this modeling effort concentrated on non-sloshing, complete expulsion (from 95 to 5% fill level) cases using either helium or gaseous methane as pressurant. Each test run has three phases: ramp, hold, and drain.

The ramp phase takes approximately 30 seconds. The tank ullage, which is initially gaseous methane at atmospheric pressure, is pressurized to 340 kPa (50 psia). The temperature of the incoming pressurant gas is maintained near 222 or 333 K (400 or 600 °R), the “cold” or “warm” pressurant cases. The drain is closed.

The hold phase also lasts approximately 30 seconds. The drain remains closed, and a small flow of pressurant maintains the ullage pressure at 340 kPa (50 psia).

During the drain phase, the drain is opened, and approximately 650 kg (1430 lb) of liquid methane is expelled, reducing the fill level from 95% to approximately 5%. The flow of pressurant gas continues to maintain the ullage pressure at 340 kPa (50 psia). The drain rate can be “fast” (~200 second drain time), “medium” (~400 s), or “slow” (~600 s).

Using the measured flow rate of pressurant gas, as well as the measured ullage pressure, temperature, and gas concentration, the test report provides the ullage mass at the end of each phase, the total amount of pressurant required, and the net amount of methane condensed or evaporated. For eight of the twelve cases, plots of fluid temperature and wall temperature as functions of height were also provided. These plots were digitized to allow comparison to the model results.

IV. GFSSP Model

Multiple GFSSP models were developed to model the tests described in the previous section. GFSSP is a network flow solver [6], in which a fluid system is discretized into nodes connected by branches. Conservation of mass and energy is solved in the nodes to calculate pressures and enthalpies (and therefore temperatures). The momentum equation is solved in the branches to calculate flow rates. Conjugate heat transfer may be added to a model with solid nodes representing the mass of tank walls. The energy equation is solved in the solid nodes to calculate wall temperatures. Conductors connect the solid nodes with each other (conduction) or with the fluid nodes (convection). Fortran user subroutines allow for convection coefficient correlations or custom heat and mass transfer processes.

An adaptive multi-node ullage model was developed for both helium and autogenous pressurization (Figure 2). Each ullage node is expanded uniformly as the ullage grows and the attached solid node also grows simultaneously. An approach with a single ullage node with multiple solid nodes, similar to the Thermal Desktop approach described in the Introduction [8], was also developed.

In both types of model, the following simplifications were made:

- Heat leak from the ambient was assumed negligible.

- The tank wall mass was treated as a perfect aluminum sphere. In reality, the tank lid was stainless steel, with an insulated inner surface that matched the curvature of the tank. Exact details of the tank lid were unavailable in [5].
- The mass of the tank rakes, diffuser, and sampling tubes was assumed negligible.
- The ullage was assumed to have a single initial temperature. This temperature was not provided by [5]. However, it was calculated using the given initial ullage mass and volume to calculate the initial density, and then determining at atmospheric pressure the temperature which provides this density.

Formulation

Pressurant Supply

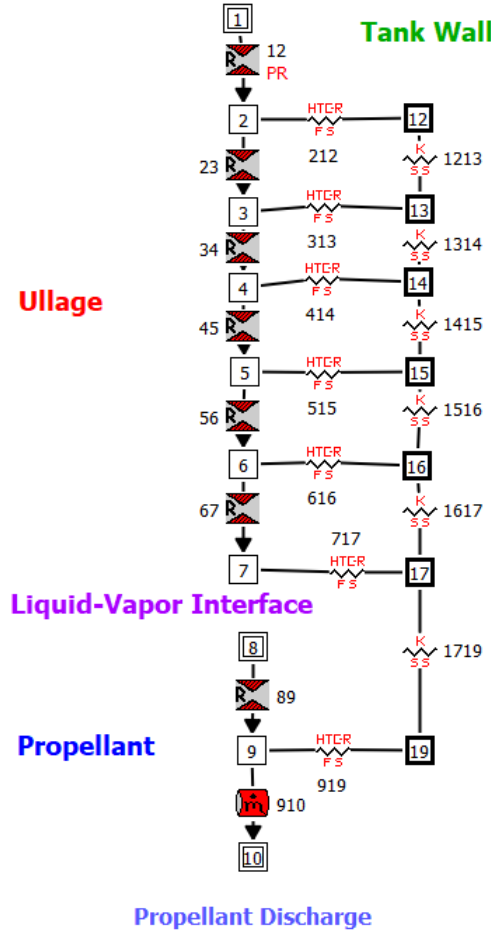


Fig. 2 GFSSP Model of K-Site Test Tank [5]

A. Multi-Node Ullage Model

Figure 2 presents the multi-node ullage model. Boundary Node 1 fixes the temperature of the incoming pressurant to the reported value. The ullage is discretized into six layers of equal height and represented by six nodes (Nodes 2 - 7). The initial pressure in these nodes is 101 kPa (14.7 psia). The initial temperature is calculated from the reported initial density as described above. The value varied from 112 to 131 K depending on the run. The ullage nodes are connected by 5 branches (Branches 23, 34, 45, 56, and 67) of nearly zero resistance. However, gravitational force is added to the momentum equation solved in these branches through a user subroutine.

Branch 12 is a pressure regulator that varies the pressurant flow rate to maintain the desired ullage pressure. The desired pressure varies linearly from 101 kPa (14.7 psia) at the beginning of the run to 340 kPa (50 psia) at the end of the ramp phase, holding 340 kPa for the remainder of the run.

The propellant is represented as a single node (Node 9). The temperature is 111.46 K, slightly sub-cooled liquid (by 0.2 K) at atmospheric pressure. Boundary Node 8 represents a pseudo-boundary between ullage and propellant. It prevents mixing of liquid and gas but applies the ullage pressure to the propellant node through the liquid surface

represented in Branch 89. The propellant drains through Fixed Flow branch 910 to exit Boundary Node 10; the flow rate is fixed based on the reported mass drained and the time for draining.

The tank wall is discretized into 7 solid nodes (Node 12, 13, 14, 15, 16, 17 & 19) with the same height as the ullage nodes and propellant node. As the tank drains, the ullage volume grows and the propellant volume shrinks. In each time step, the ullage is re-discretized into layers of equal height. At the start of the run, when ullage is 5% of total volume, each layer is 3.3 cm (0.11 ft) high. At the end of the run, when ullage occupies 95% of the total volume, each layer is 19.5 cm (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. The heat transfer areas of the convection and conduction conductors are also adjusted at this time.

1. Algorithm for Adaptive Fluid Node

Before the first time step of the model run, the user subroutine creates a tanking table. Based on the equations for the geometry of a sphere, the cumulative volume, wall surface area, wall mass, and liquid level surface area are calculated as a function of height from the bottom of the tank. In each time step, these values are then interpolated based on the changing ullage and propellant volumes. Although it would also be possible to calculate these quantities directly from the equations for a sphere, the interpolation scheme requires fewer calculation steps and can be easily adapted to read in a tanking table, if this algorithm is ever applied to a tank with irregular geometry.

In each time step, the propellant volume is updated based on the mass of liquid methane drained from the tank in the previous time step:

$$\Delta V_{prp} = \frac{-\dot{m}}{\rho_{liq} \Delta \tau} \quad (1)$$

The tanking table is then used to interpolate the height of the liquid propellant and the height of the ullage. The ullage space is divided into six layers of equal height. The tanking table is used to interpolate at the bottom height of each layer the cumulative tank volume and the cross-sectional area. These values are then used to determine the updated volume of each ullage node (Nodes 2 – 7) and the cross-sectional area of each restriction (Branches 23, 34, 45, 56, 67, and 89).

The pressure of the bottom ullage node (Node 7) calculated in the previous time step is added to the hydrostatic head, based on the interpolated height of the propellant, and this pressure is fixed at Pseudo-Boundary Node 8:

$$P_{psb} = P_{ull} + \rho_{liq} g h_{prp} \quad (2)$$

The pressure-volume work done by the expansion of each ullage node during draining is calculated and set as a heat sink in each node's energy equation.

2. Algorithm for Adaptive Solid Node

In the first time step, the solid node specific heat property file is numerically integrated by the trapezoidal rule to create a table of solid energy, E , as a function of absolute temperature. As the tank drains and the ullage nodes are re-discretized, the solid nodes are also re-discretized (Figure 3). The mass of each solid node is interpolated from the tanking table, and the heat transfer areas in the convection and conduction conductors are updated.

As exaggerated in Figure 3, when the solid nodes are re-discretized at the beginning of each time step, a portion of the colder solid node below it is now re-distributed to the growing solid node. An energy balance is performed using the solid energy table to calculate a new temperature of the solid node to be used in the heat transfer calculations in the current time step:

$$m_i^{\tau-\Delta\tau} E(T_i^{\tau-\Delta\tau}) + m_{i+1}^{\tau-\Delta\tau} E(T_{i+1}^{\tau-\Delta\tau}) = m_i^{\tau} E(T_i^{\tau}) \quad (3)$$

where the mass values on the left-hand side of (3) represent the portions of the masses of the solid nodes bounded by the limits of the solid node in the current time step. For example, in Figure 3 the new temperature of solid node 15 is based on an energy balance of most of the mass of solid node 15 and a small portion of the mass of solid node 16 at the end of the previous time step.

3. Heat Transfer from ullage to wall and propellant

This paper investigates the use of natural and mixed convection correlations in calculating the heat transfer between ullage to wall and ullage to propellant.

For natural convection, heat transfer between ullage and wall is given by:

$$Nu = 0.54 Ra^{0.25} \quad (4)$$

and heat transfer between ullage and propellant is given by:

$$Nu = 0.27 Ra^{0.25} \quad (5)$$

For mixed-convection the Woodfield correlation [9] is applied:

$$Nu_H = 0.56 Re_D^{0.67} + 0.104 Ra_H^{0.352} \quad (6)$$

Thermal Desktop offers this correlation as an option for simulating Tank Pressurization.

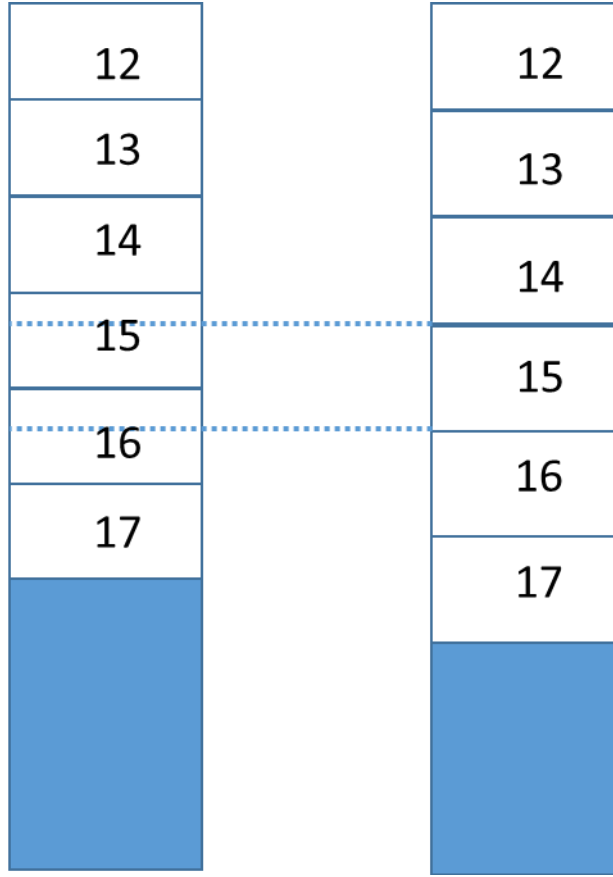


Fig. 3 Re-discretization of solid nodes as tank drains (scale exaggerated)

4. Condensation at the wall

It is necessary to model condensation for autogenous pressurization when gaseous methane is used to pressurize liquid methane. Condensation takes place at the wall when the wall temperature is below saturation temperature.

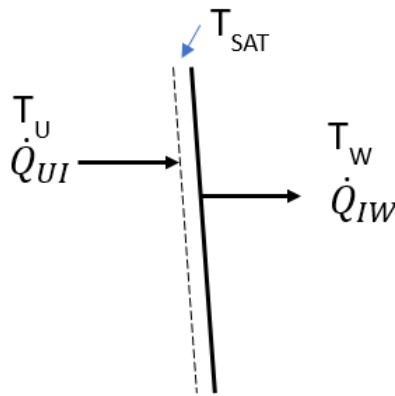


Fig. 4 Condensation model at the wall

A schematic of the condensation model at the wall is shown in Figure 4. It is assumed that condensation occurs in a layer adjacent to the wall when the wall temperature is below the saturation temperature, and the layer is also assumed to be at saturation temperature.

The heat transfer from the ullage to the saturated layer is given by:

$$\dot{Q}_{UI} = [h_c A]_{U-I} (T_{ullage} - T_{SAT}) \quad (7)$$

where the heat transfer coefficient, h_c is computed from Equation (4).

The heat transfer from the saturated layer to wall is given by:

$$\dot{Q}_{IW} = [h_c A]_{I-W} (T_{SAT} - T_w) \quad (8)$$

h_c of Equation (8) is evaluated from the following equation which is known as the Dhir-Lienhard [10] correlation of condensation heat transfer:

$$Nu_D = C \left[g \frac{\rho_f (\rho_f - \rho_g) h'_{fg} D^3}{\mu k \Delta T} \right]^{\frac{1}{4}} \quad (9)$$

The condensation rate is calculated from:

$$\dot{m}_{cond} = \frac{\dot{Q}_{IW} - \dot{Q}_{UI}}{h_{fg}} \quad (10)$$

5. Condensation at ullage-propellant interface

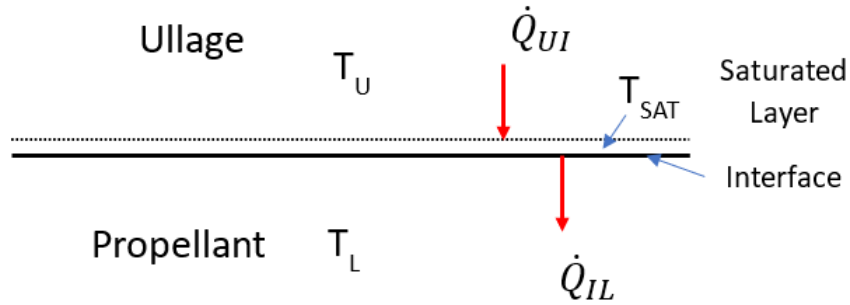


Fig. 5 Condensation model at the ullage propellant interface

The condensation model at the liquid surface is shown in Figure 5. Condensation occurs at the ullage to propellant interface when $\dot{Q}_{IL} > \dot{Q}_{UI}$. The condensation rate is given by:

$$\dot{m}_{cond} = \frac{\dot{Q}_{IL} - \dot{Q}_{UI}}{h_{fg}} \quad (11)$$

$$\dot{Q}_{UI} = h_{c,UI} A (T_U - T_{SAT}) \quad (12)$$

$$\dot{Q}_{IL} = h_{c,IL} A (T_{SAT} - T_L) \quad (13)$$

$h_{c,UI}$ and $h_{c,IL}$ are computed from Equation (5) using vapor and liquid properties respectively.

For autogenous pressurization, there is no presence of non-condensable gas in the ullage, and T_{SAT} , which is a function of ullage pressure, is generally higher than liquid methane temperature, T_L . Therefore, condensation takes place during entire operation consisting of ramp, hold and drain. On the other hand, for helium pressurization, due to presence of a non-condensable in gaseous methane in the ullage, T_{SAT} is a function of the partial pressure of GCH_4 which decreases as helium concentration increases. Initially, helium concentration is low and methane concentration is higher and therefore T_{SAT} is higher than T_L and condensation takes place during the ramp and hold phases. However, during draining helium concentration increases and methane concentration decreases; T_{SAT} starts decreasing and eventually becomes less than T_L and evaporation starts. The test data has provided the net amount of condensation and evaporation in each phase of the test cases of helium pressurization.

B. Single-Node Ullage Model with multiple solid nodes.

To explore the effects of the Thermal Desktop approach employed in [8], an additional model was developed for the helium pressurization tests. Figure 6 shows a GFSSP model with a single ullage node (Node 2). This approach models the ullage as well-mixed with uniform temperature (no stratification). The pressurant supply (Boundary Node 1), pressure regulator (Branch 12), propellant node (Node 4), and drain rate (Fixed Flow Branch 45) are handled in the same way as for the multi-node ullage model.

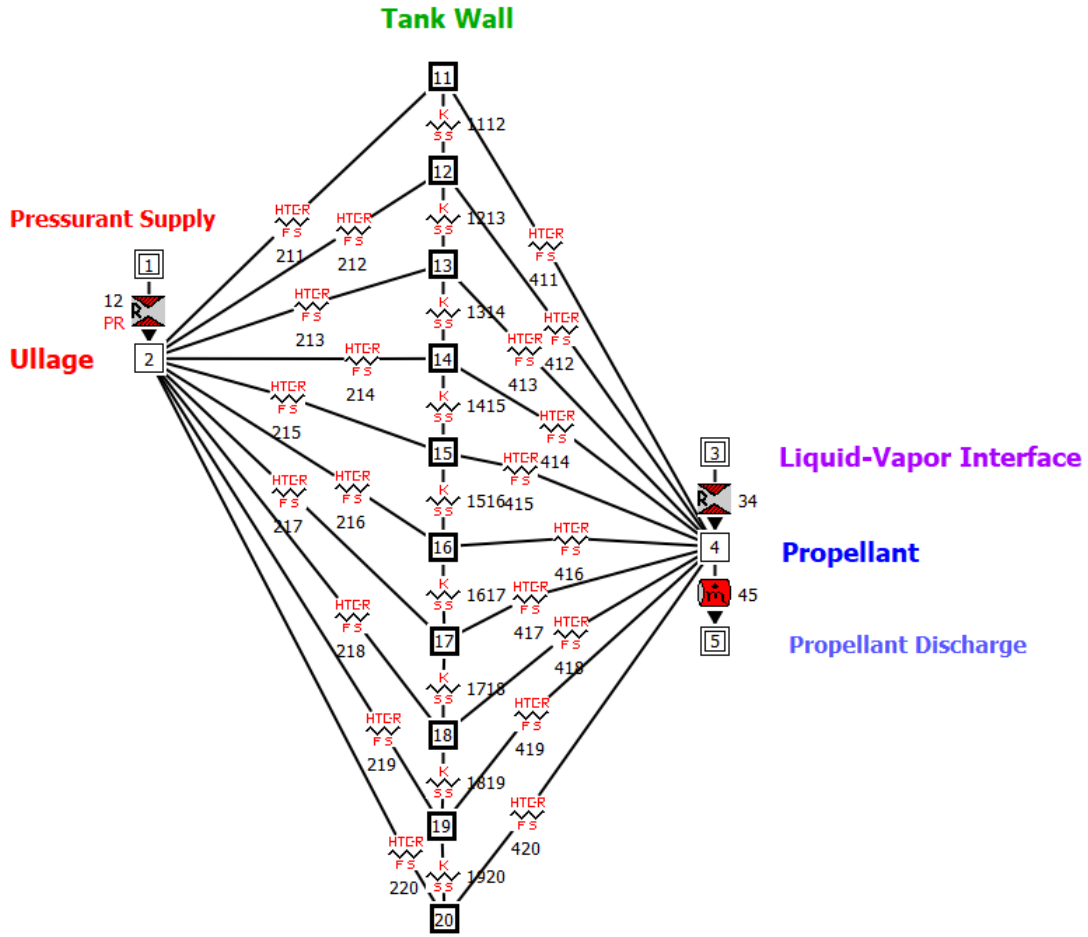


Fig. 6 Model with Single-Node Ullage and Multiple Solid Nodes

The tank wall is discretized into 10 layers (Solid Nodes 11-20). These solid nodes have fixed geometry. Each represents the mass of a 15.2 cm (0.5 ft) slice of the tank wall. As the tank drains, the volume of ullage node 2 will grow, and that of propellant node 4 will shrink. As the liquid level decreases, the heat transfer areas of the ullage side convection conductors increase one-by-one from 0.0 to 0.73 m² (7.85 ft²), and the propellant side conductors likewise decrease. The ullage-side convection coefficient is calculated from the Woodfield correlation. The propellant-side convection coefficient is arbitrarily set to 20,400 W/m²-K (1 BTU/s-ft²-R); this ensures that the tank wall covered with liquid is at liquid temperature.

V. Results and Discussion

A. Helium Pressurization

Several sets of runs were made with the helium pressurization models, exploring the effects of heat transfer assumptions on helium consumption, as well as on predicted ullage and wall temperatures.

1. Multi-Node Ullage Model with Natural Convection

This series of model runs assumes that the ullage is initially pure helium rather than gaseous methane. There is no attempt to model condensation or evaporation. The ullage-to-wall and ullage-to-propellant heat transfer is calculated with the natural convection correlations in equations (4) and (5). Table 1 summarizes the predicted pressurant consumption for the six helium runs. Consumption is under-predicted by 7-12%, with a mean error of -10%, an improvement from the -16% error from the earlier single-node ullage with single-node wall model [7]. Note that the agreement is slightly better for the runs with cold helium.

Table 1: Helium Consumption Predicted by Multi-Node Model with Natural Convection

Run	He Inlet T (K)	Drain Time (s)	Measured He Mass (kg)	Predicted He Mass (kg)	Error (%)
37	229	223	1.990	1.845	-7%
36	226	389	2.096	1.936	-8%
33	231	622	2.145	1.974	-8%
42	324	224	1.895	1.674	-12%
41	331	390	2.000	1.791	-11%
40	311	599	2.091	1.868	-11%

Figure 7 illustrates the predicted and measured wall temperatures at the end of each of the four runs plotted in [5]. The mean absolute error (MAE) in temperature was 2 - 6 K. The mean absolute percentage error (MAPE) was 1.6 – 4.1%.

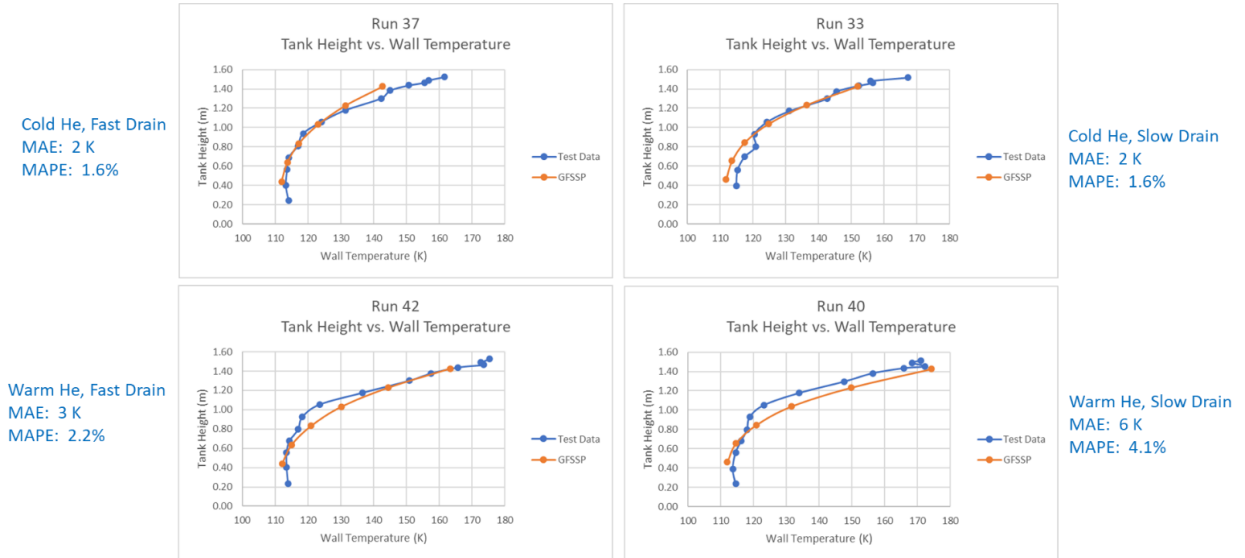


Fig. 7 Predicted wall temperatures (K), assuming natural convection

Figure 8 shows the predicted and measured ullage gas temperatures at the end of each run. MAE was 5 – 7 K, and MAPE was 3.5 – 9.1%. In general, the predicted ullage gas temperatures are too warm, leading to the under-prediction of helium consumption shown in Table 1.

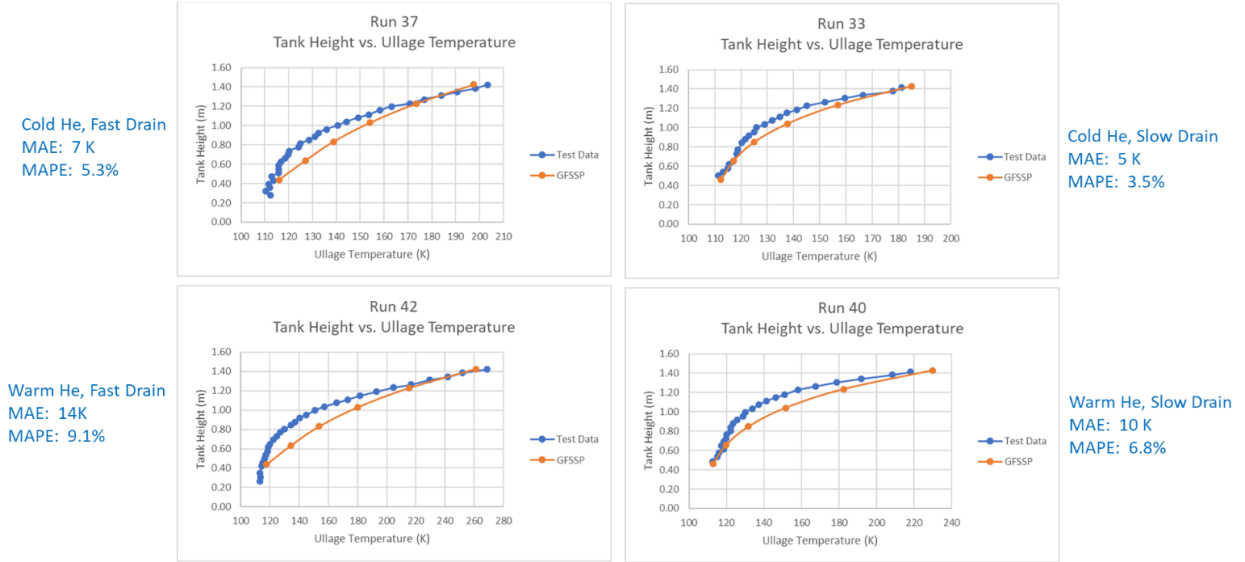


Fig. 8 Predicted ullage temperatures (K), assuming natural convection

2. Multi-Node Ullage Model with Mixed Convection

As in the above model, this series of model runs assumes that the ullage is pure helium, with no methane condensation or evaporation. However, the ullage-to-wall heat transfer is now calculated with the Woodfield mixed convection correlation in equation (6). Table 2 summarizes the predicted pressurant consumption. The error in predicted consumption varies from -5% to +5%, with a mean error of 0%, an improvement from the -10% error shown above when using the natural convection correlations. Note that over-prediction occurs in the fast-drain cases (Runs 37 and 42), when the flow rate of helium is greater, leading to higher convection coefficients and more cooling of the helium. On the other hand, under-prediction occurs in the slow-drain cases (Runs 33 and 40).

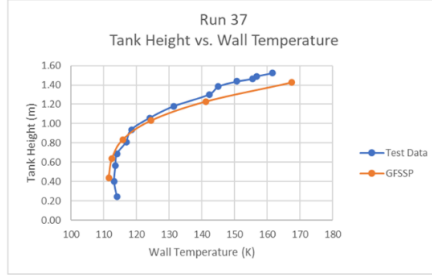
Table 2: Helium Consumption Predicted by Multi-Node Model with Mixed Convection

Run	He Inlet T (K)	Drain Time (s)	Measured He Mass (kg)	Predicted He Mass (kg)	Error (%)
37	229	223	1.990	2.080	+5%
36	226	389	2.096	2.082	-1%
33	231	622	2.145	2.059	-4%
42	324	224	1.895	1.997	+5%
41	331	390	2.000	1.994	-0.3%
40	311	599	2.091	1.988	-5%

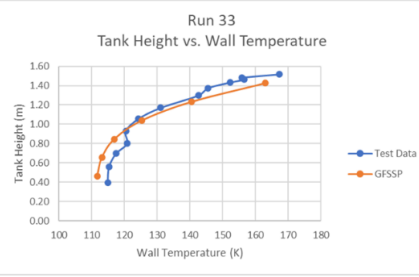
Figure 9 presents the predicted and measured wall temperatures at the end of each run. The MAE in temperature was 5-10 K. The MAPE was 3.4 – 6.5%. The error in wall temperature was greatest for the warm helium cases.

Figure 10 shows the predicted and measured ullage gas temperatures at the end of each run. MAE was 2 – 16 K, and MAPE was 1.8 – 8.6%. The error in ullage temperature was greatest for the fast drain cases, when the predicted mixed convection coefficients were largest.

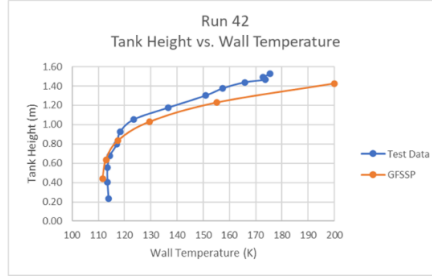
Cold He, Fast Drain
MAE: 5 K
MAPE: 3.6%



Cold He, Slow Drain
MAE: 5 K
MAPE: 3.4%



Warm He, Fast Drain
MAE: 10 K
MAPE: 6.5%



Warm He, Slow Drain
MAE: 9 K
MAPE: 6.3%

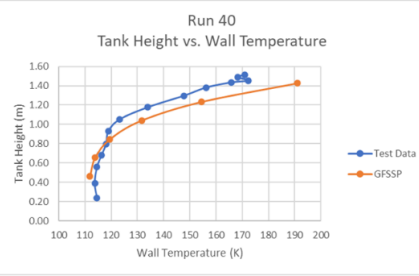
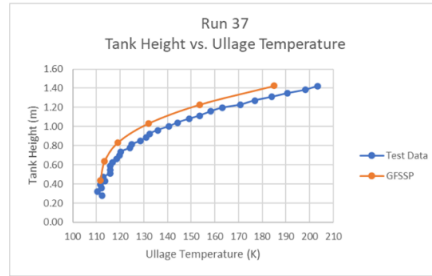
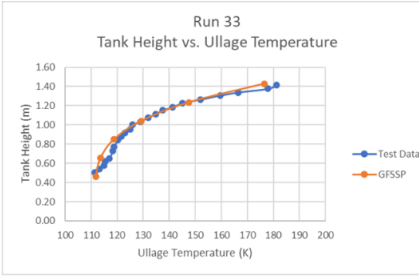


Figure 9: Predicted wall temperatures (K), assuming mixed convection

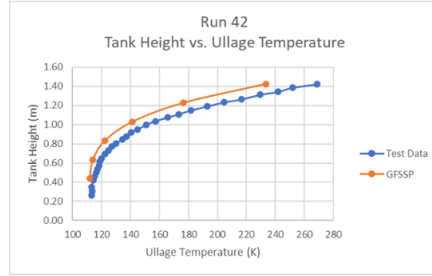
Cold He, Fast Drain
MAE: 10K
MAPE: 6.4%



Cold He, Slow Drain
MAE: 2 K
MAPE: 1.8%



Warm He, Fast Drain
MAE: 16 K
MAPE: 8.6%



Warm He, Slow Drain
MAE: 4 K
MAPE: 2.3 %

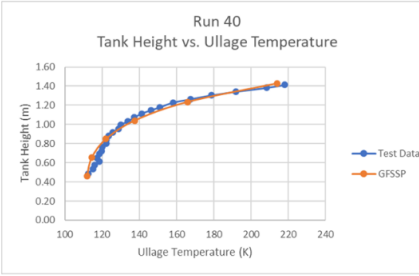


Figure 10: Predicted ullage temperatures (K), assuming mixed convection

3. Multi-Node Ullage Model with Mixed Convection and Mass Transfer

In this series of model runs the ullage is initialized as pure gaseous methane. Mass transfer through condensation or evaporation at the propellant surface is allowed to occur, as described in equations (11) – (13). The ullage-to-wall heat transfer is calculated with the Woodfield mixed convection correlation.

Figure 11 plots for Run 33 the temperature at the bottom of the ullage in comparison to the propellant temperature and the saturation temperature at the partial pressure of the gaseous methane. For the first 81 seconds (during ramp, hold, and the start of drain), the propellant is colder than the saturation temperature.

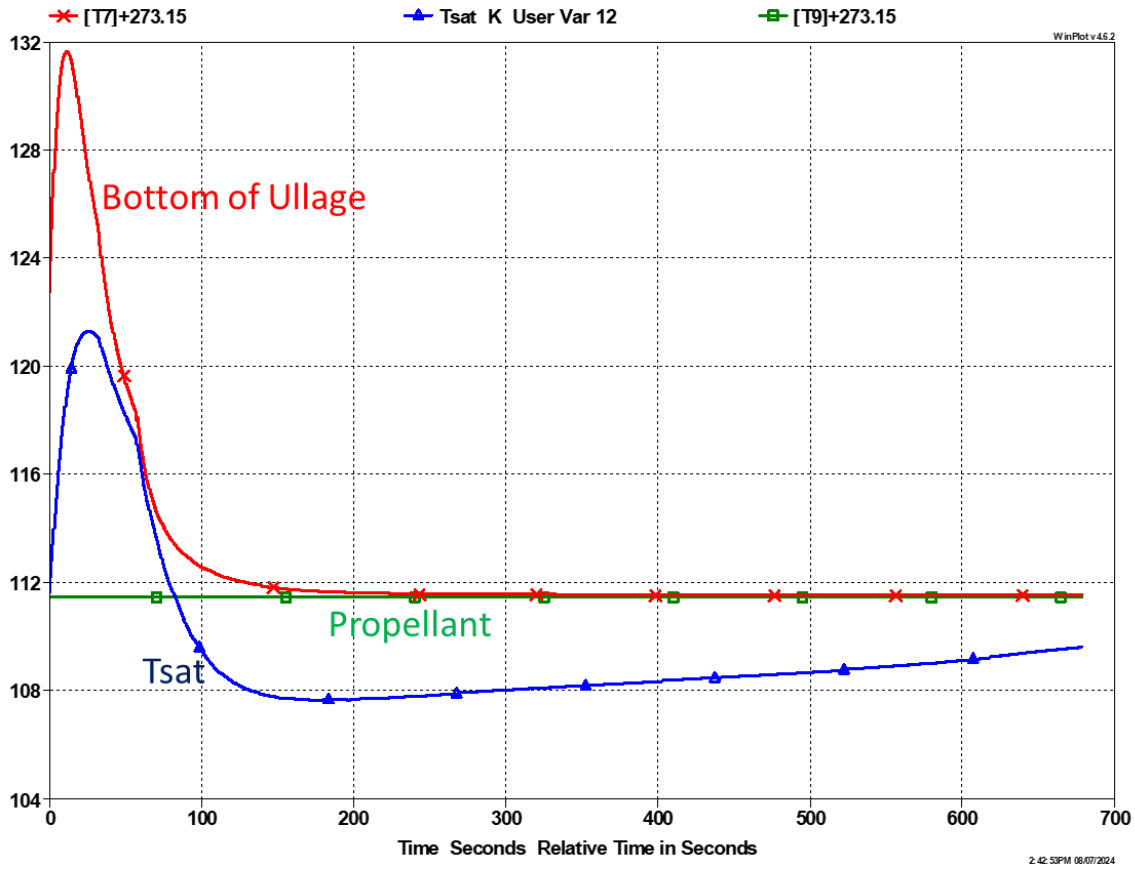


Fig. 11 Ullage, propellant, and saturation temperatures (K) for Run 33

Figure 12 plots the calculated methane mass transfer rate from ullage to propellant for Run 33. Positive values indicate condensation; negative, evaporation. Condensation occurs during ramp, hold, and the start of drain, but at 85 seconds, shortly after the saturation temperature drops below the propellant temperature, the mass transfer switches to evaporation.

Table 3 summarizes the predicted pressurant consumption. The error in predicted consumption varies from -8% to + 3%, with a mean error of -3%. In general, compared to the results of the mixed convection model without mass transfer, predicted helium consumption is reduced by three percentage points. Note that over-prediction occurs in the fast-drain cases (Runs 37 and 42); on the other hand, under-prediction occurs in the medium- and slow-drain cases.

Looking only at the ramp phase, predicted helium consumption increased by six percentage points in each run. For example, the error in helium consumption for the ramp phase of Run 33 improved from -37% without mass transfer to -31% with mass transfer. This is consistent with condensation removing gaseous methane during the ramp phase, therefore requiring more helium to pressurize the ullage.

Table 4 summarizes the predicted condensation during the ramp phase. The model under-predicts condensation by an average of 74%. This may indicate that the liquid side heat transfer coefficient is too small.

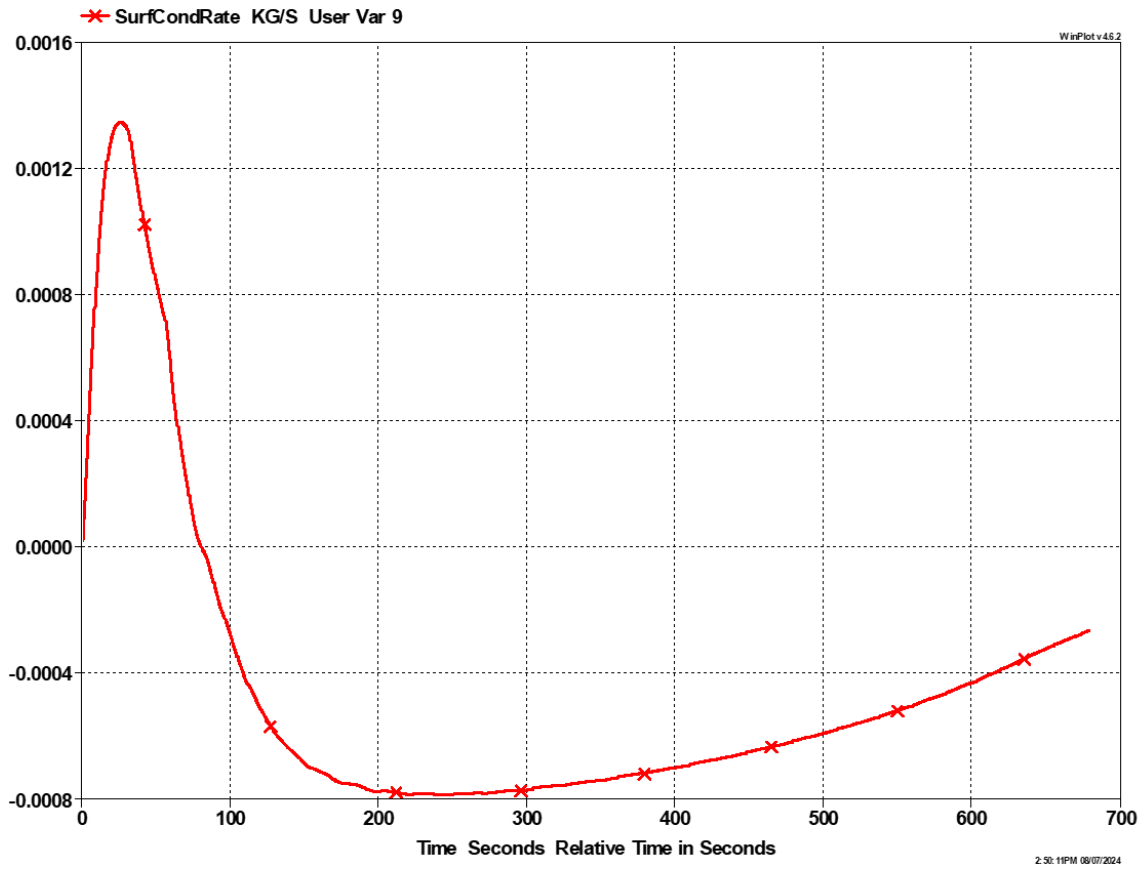


Fig. 12 Ullage-to-propellant methane mass transfer rate (kg/s) for Run 33

Table 3: Helium Consumption Predicted by Multi-Node Model with Mixed Convection and Mass Transfer

Run	He Inlet T (K)	Drain Time (s)	Measured He Mass (kg)	Predicted He Mass (kg)	Error (%)
37	229	223	1.990	2.04	+2%
36	226	389	2.096	2.03	-3%
33	231	622	2.145	2.00	-7%
42	324	224	1.895	1.96	+3%
41	331	390	2.000	1.94	-3%
40	311	599	2.091	1.93	-8%

Table 4: Predicted Methane Condensation During Ramp by Multi-Node Model with Mixed Convection and Mass Transfer

Run	He Inlet T (K)	Drain Time (s)	Measured CH4 Condensation (kg)	Predicted CH4 Condensation (kg)	Error (%)
37	229	223	0.105	0.029	-72%
36	226	389	0.135	0.031	-77%
33	231	622	0.112	0.031	-72%
42	324	224	0.108	0.031	-71%
41	331	390	0.118	0.030	-75%
40	311	599	0.119	0.030	-75%

Table 5: Predicted Methane Mass Transfer During Hold by Multi-Node Model with Mixed Convection and Mass Transfer

Run	He Inlet T (K)	Drain Time (s)	Measured CH4 Condensation (kg)	Predicted CH4 Condensation (kg)	Error (%)
37	229	223	0.010	0.023	130%
36	226	389	-0.006 (evap)	0.026	530%
33	231	622	0.038	0.025	-34%
42	324	224	0.029	0.025	-14%
41	331	390	0.013	0.027	108%
40	311	599	-0.009 (evap)	0.026	390%

Table 5 shows the methane mass transfer during the hold phase of each run. Note that the test data indicated evaporation for Runs 36 and 40; the model predicted condensation for all the runs. Errors ranged from -34% to +530%, with a mean of +185%. It is noted that the magnitude of the measured values is small; the report [5] does not provide an estimated uncertainty in these values.

Table 6 summarizes the net methane evaporation during the drain phase; a net value is provided because the model predicts condensation for approximately the first 20 seconds of the drain period, as seen in Figure 12. The model over-predicts evaporation by 20 - 340%, with a mean error of 120%. The over-prediction of evaporation could indicate that the liquid side heat transfer coefficient is too small, as also suggested by the under-prediction of condensation during the ramp phase.

Figure 13 shows the predicted and measured wall temperature at the end of each run. The MAE in temperature was 4 – 10 K. The MAPE was 3 - 6%. The error in wall temperature was greatest for the warm helium cases. It is noted that these results are only slightly different from the wall temperatures predicted by the mixed convection model without mass transfer, shown in Figure 9.

Table 6: Predicted Methane Net Evaporation During Drain by Multi-Node Model with Mixed Convection and Mass Transfer

Run	He Inlet T (K)	Drain Time (s)	Measured CH4 Evaporation (kg)	Predicted CH4 Evaporation (kg)	Error (%)
37	229	223	0.131	0.271	107%
36	226	389	0.177	0.319	80%
33	231	622	0.296	0.356	20%
42	324	224	0.061	0.266	340%
41	331	390	0.206	0.321	56%
40	311	599	0.159	0.354	123%

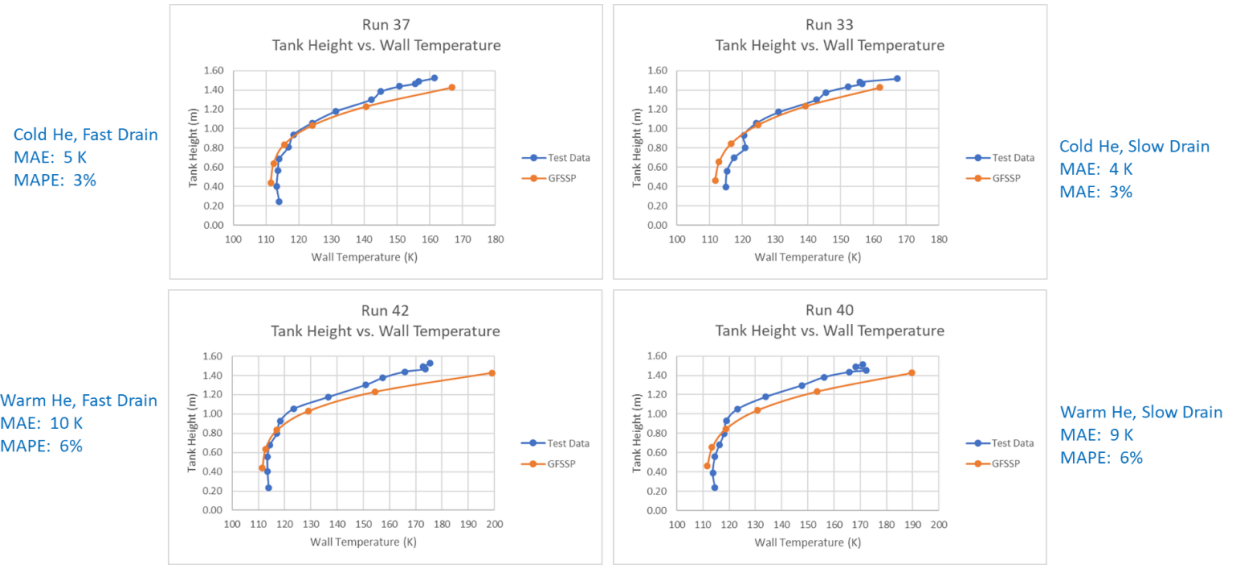


Fig. 13 Predicted wall temperatures (K), assuming mixed convection and mass transfer

Figure 14 illustrates the predicted and measured ullage gas temperatures at the end of each run. The MAE in temperature was 3 – 17 K. The MAPE was 2 – 9%. The error in ullage temperature was greater for the fast drain cases. Again, these values are very similar to the ullage temperatures predicted by the mixed convection model without mass transfer, shown in Figure 10.

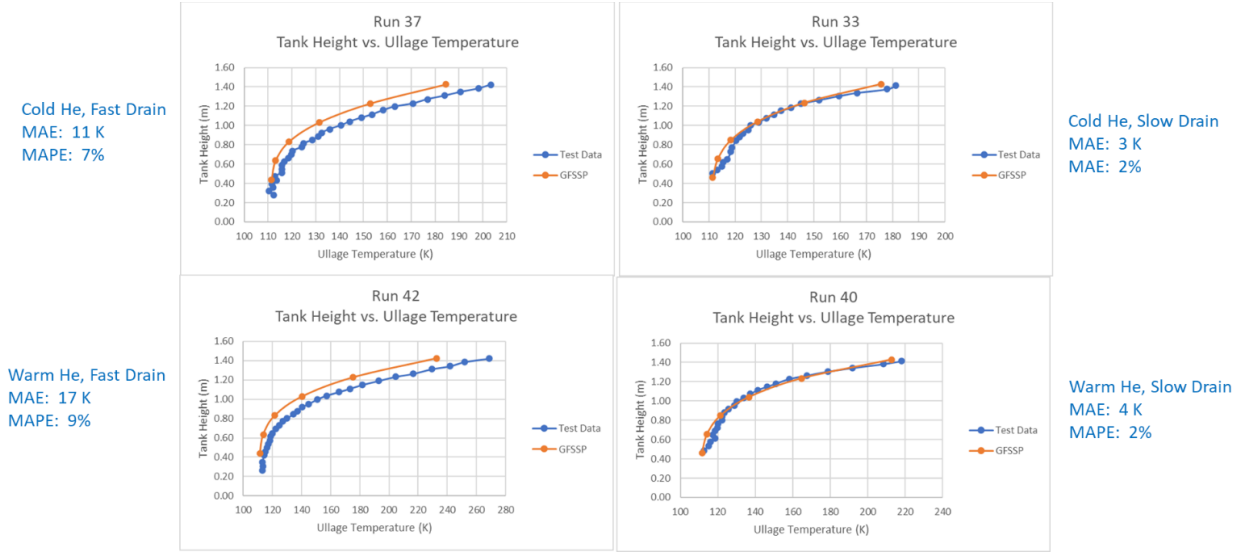


Fig. 14 Predicted ullage temperatures (K), assuming mixed convection and mass transfer

4. Single-Node Ullage Model with Multiple Solid Nodes and Mixed Convection

This series of model runs utilizes the single-node ullage model illustrated in Figure 6. The model assumes that the ullage is pure helium, with no methane condensation or evaporation. The ullage-to-wall and ullage-to-propellant heat transfer is calculated with the Woodfield mixed convection correlation. Table 7 summarizes the predicted pressurant consumption. The error in predicted consumption varies from -4% to +4%, with a mean error of -0.2%. Note that over-prediction occurs in the fast-drain cases (Runs 37 and 42). On the other hand, under-prediction occurs in the slow-drain cases (Runs 33 and 40). Also note that an earlier version of this model used the Woodfield mixed convection correlation for ullage-to-wall, but the Ring natural convection correlation for ullage-to-propellant. In that case, the predicted helium consumption for each run was decreased by approximately 2%, consistent with less heat transfer to the cold liquid surface.

Table 7: Helium Consumption Predicted by Single-Node Ullage Model with Mixed Convection

Run	He Inlet T (K)	Drain Time (s)	Measured He Mass (kg)	Predicted He Mass (kg)	Error (%)
37	229	223	1.990	2.072	+4%
36	226	389	2.096	2.091	0%
33	231	622	2.145	2.095	-2%
42	324	224	1.895	1.952	+3%
41	331	390	2.000	1.970	-2%
40	311	599	2.091	2.001	-4%

Figure 15 plots the predicted and measured wall temperatures at the end of each run. The predicted wall temperatures from the multi-node ullage model are also plotted for comparison. Whereas the MAE in temperature for the multi-node model was 5 – 10 K, for the single-node ullage the MAE increased to 8 – 12 K. Moreover, the shape of the single-node ullage model's predicted temperature profile does not match the test data. This is attributed to the lack of

ullage gas temperature stratification when the ullage is modeled as a single, well-mixed node. Also, incorporation of parasitic heat load, particularly from the top of the tank, could have improved the wall temperature prediction for single ullage node case.

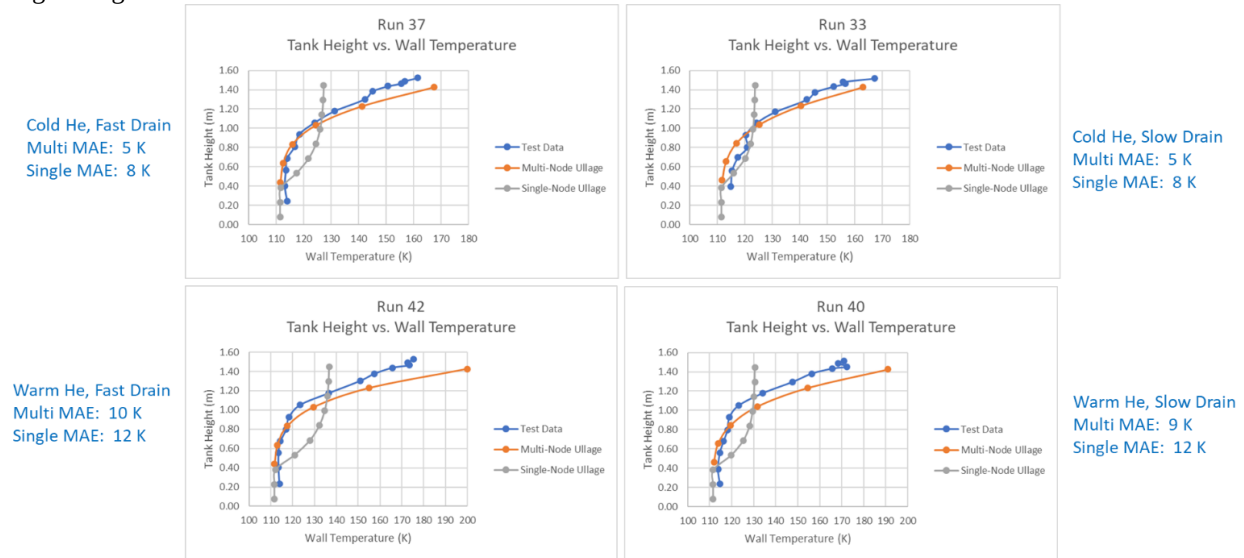


Fig. 15 Predicted wall temperatures (K), assuming mixed convection, for both single-node and multi-node ullage models

B. Autogenous Pressurization

Six test cases of autogenous pressurization, where gaseous methane was used as pressurant, were reported [5]. Experiments were conducted with two different inlet temperatures: colder (about 226 K) and warmer (about 340 K). For each temperature, experiments were performed for three different propellant drain rates. During each experiment the tank fill level was reduced from 95% fill level to approximately 5% fill level. For the fastest drain rate, the tank drains in about 230 seconds; for intermediate rate, the tank drains in about 405 seconds. It took about 635 seconds to drain at the slowest propellant flow rate. All six cases were simulated using the natural convection correlation of Ring [1] and mixed convection correlation of Woodfield [9].

The growth of the ullage volume and reduction of the propellant volume for Run 6 (colder inlet temperature and slowest drain rate) is shown in Figure 16. It may be noted that draining starts after the completion of the ramp and hold periods. The propellant flowrate was held constant during draining.

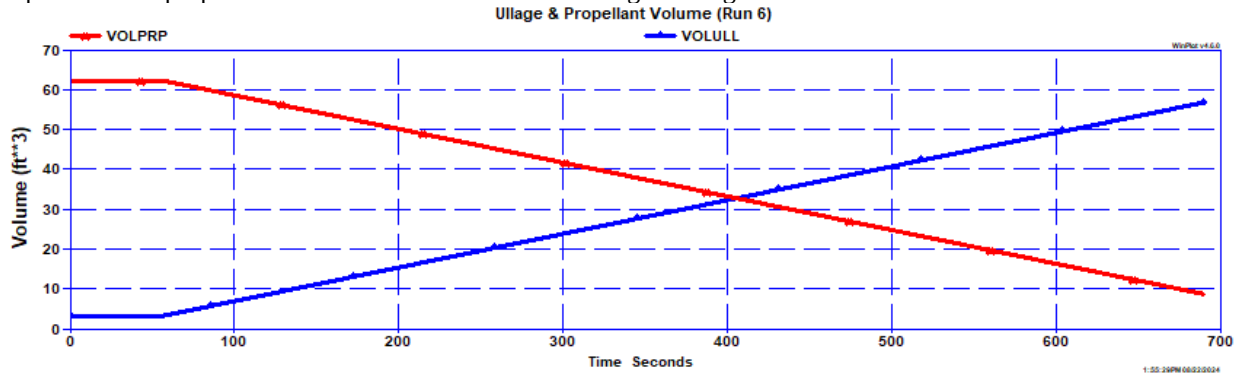


Fig. 16 Predicted Ullage and Propellant Volume (ft³) for Run 6 (colder inlet temperature and slowest drain rate)

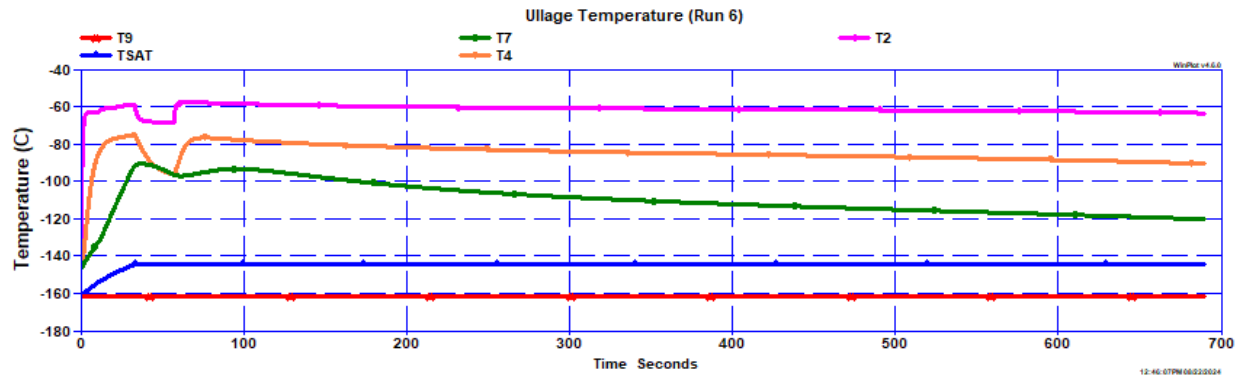


Fig. 17 Predicted saturation temperature (°C) at ullage pressure (Blue), liquid temperature (Red) and ullage temperatures at various levels (Green, Orange, and Pink)

The ullage temperatures at three different levels along with the liquid temperature and saturation temperature at ullage pressure are shown in Figure 17 for Run 6. Note that the heights and volumes of the ullage nodes vary over time as the tank drains. Thus, the temperature of Node 7 (Green line) represents the ullage temperature in the bottom 1/6 of the ullage height. Likewise, Node 2 (Pink line) covers the top 1/6 of the ullage height, and Node 4 (Orange line) ranges from 50% to 66.7% of the ullage height. Figure 17 demonstrates that stratification can be predicted by multi-node modeling of ullage. Ullage temperature rises during the ramp period because ullage pressure rises from atmospheric pressure to 340 kPa (50 psia), and because the incoming pressurant is warmer than the initial temperature. During the hold period, temperatures in the ullage node are reduced due to heat transfer to the cold wall and to the cold liquid surface.

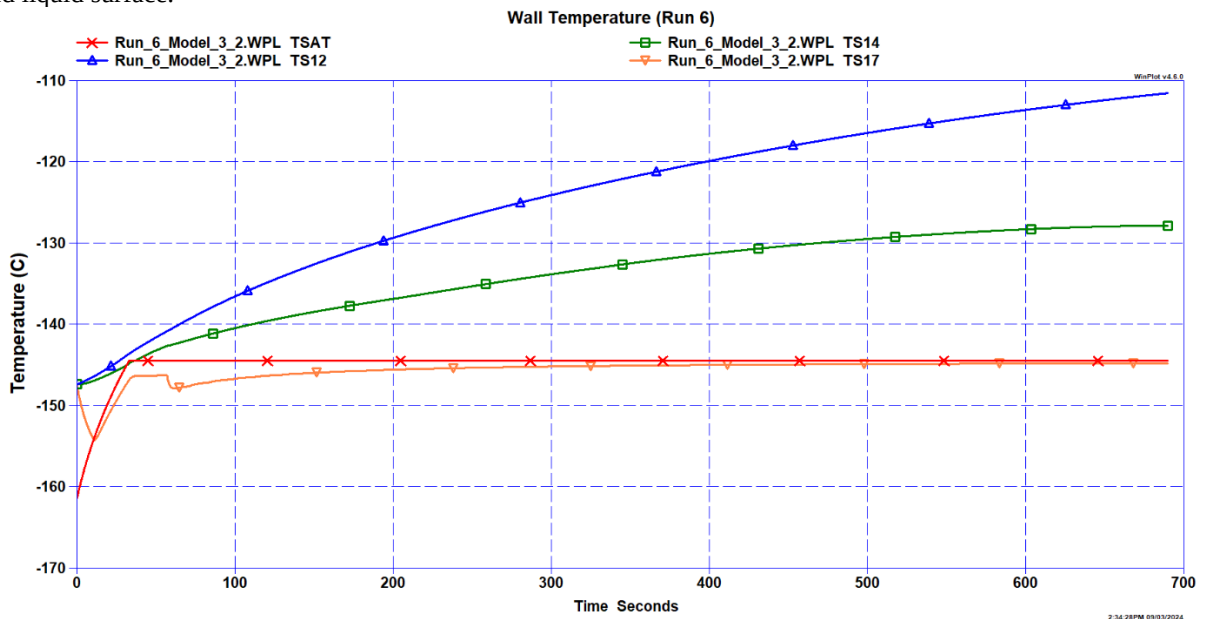


Fig. 18 Saturation temperature (°C) at ullage pressure (Red), and ullage wall temperatures at various levels (Orange, Green, and Blue)

The saturation temperature at ullage pressure and predicted ullage wall temperatures are shown in Figure 18. It may be noted that the wall temperature in the lowest 1/6 of the ullage height is lower than the saturation temperature and therefore condensation will occur at the wall.

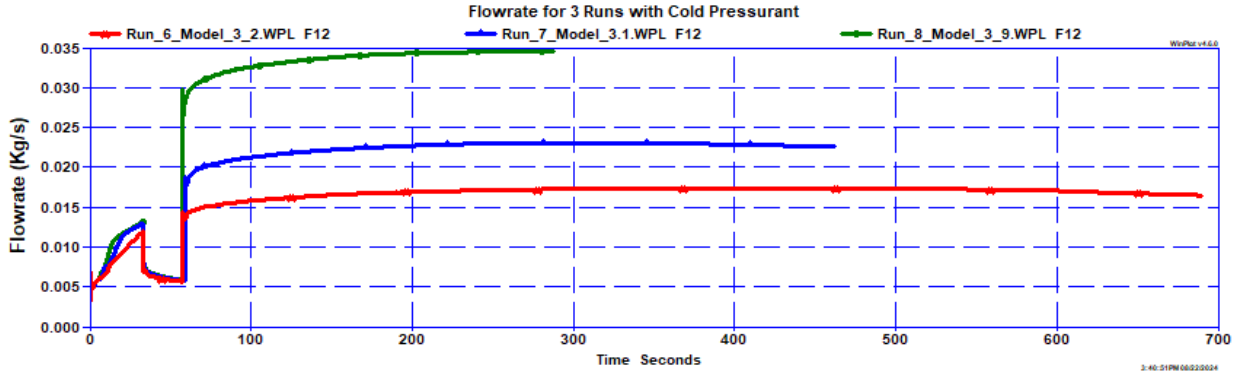


Fig. 19 Predicted pressurant flowrate (kg/s) for three runs with slow, medium, and fast drain rates

Predicted flowrates of gaseous methane entering the tank for pressurizing liquid methane for Run 6 (Slow Drain), Run 7 (Intermediate Drain), and Run 8 (Fast Drain) are shown in Figure 19. The flowrates increase during the ramp and fall to a very low value during the hold period and rapidly rise during draining. The required flowrate to maintain a constant ullage pressure is higher for faster drain rates. In each case the flowrate reaches a nearly steady state value.

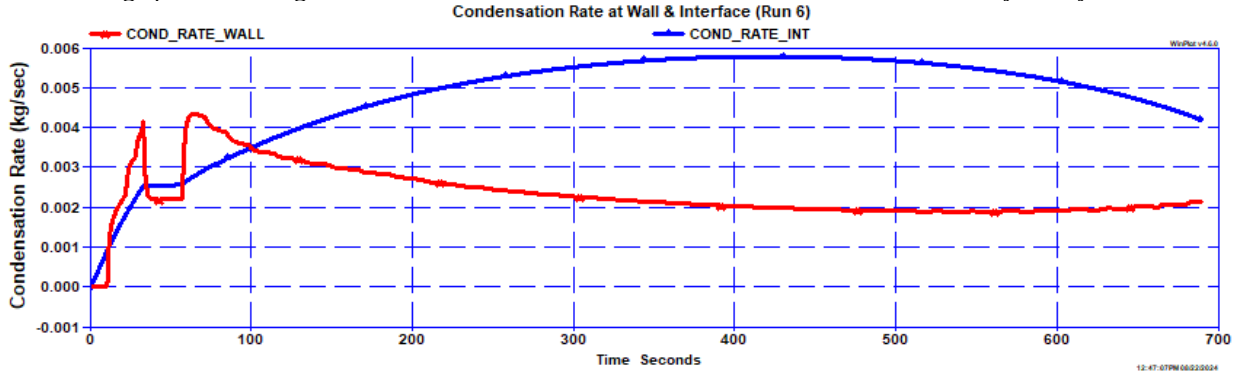


Fig. 20 Predicted condensation rate (kg/s) at the wall (Red) and interface (Blue) for Run 6

Predicted condensation rates at the wall and propellant interface for are shown in Figure 20 for Run 6. The condensation rate at the interface is significantly higher than the wall condensation rate. The condensation rate at the interface is calculated from equation (7), which implies that the heat transfer from interface to liquid, Q_{IL} , is greater than the heat transfer from ullage to interface, Q_{UI} . The predicted heat transfer coefficients on the two sides of the interface are shown in Figure 21. Q_{IL} is larger than Q_{UI} because the heat transfer coefficient on the liquid side is predicted to be about 24 times larger than on the vapor side.

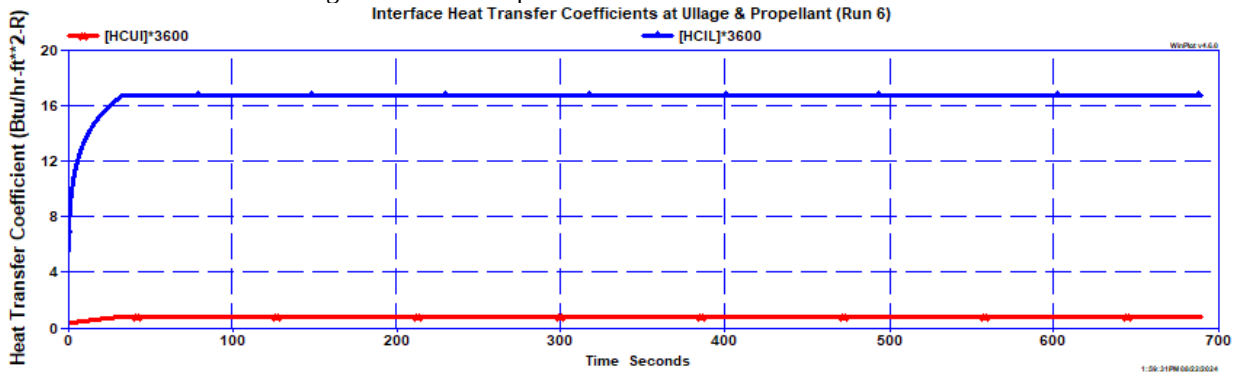


Fig. 21 Predicted heat transfer coefficients (BTU/hr-ft²-R) on the liquid and vapor sides of the liquid-vapor interface.

Predicted cumulative GCH4 consumptions for fast, intermediate, and slow drain are shown in Figure 22. During the ramp and hold periods, GCH4 consumptions are practically identical for the three runs. During draining, the

consumption rate is proportional to the draining rate. Predicted cumulative condensation for fast, intermediate, and slow drain are shown in Figure 23. The condensation rates are also proportional to the draining rate.

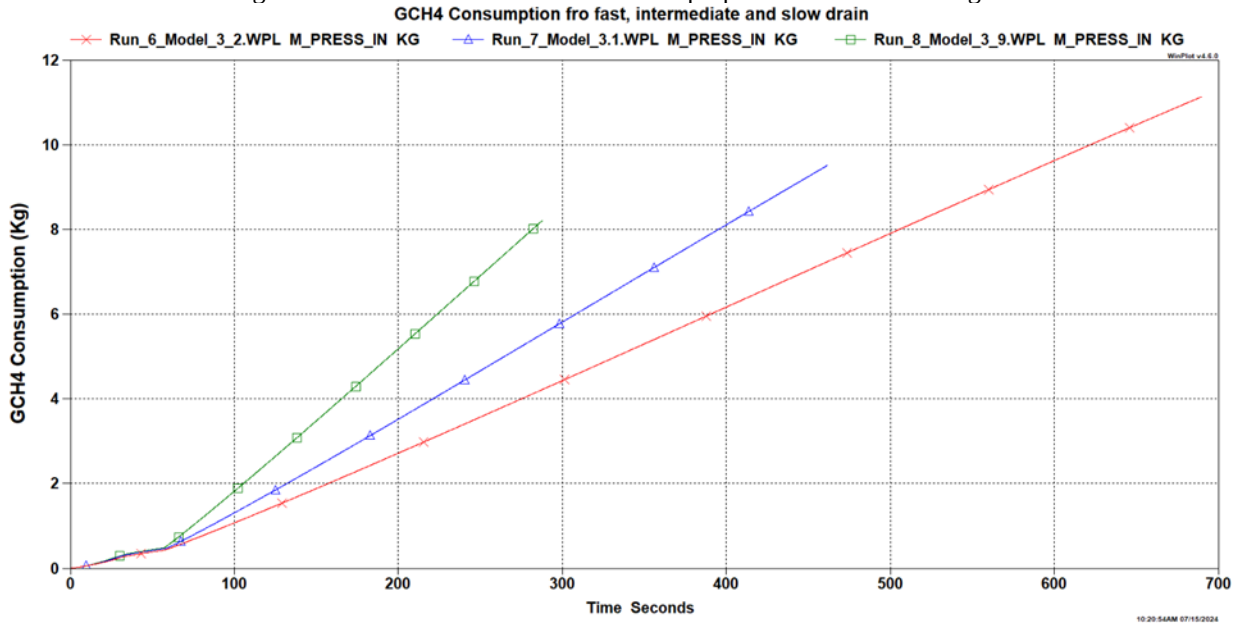


Fig. 22 Predicted GCH4 consumption (kg) for fast, intermediate, and slow drain

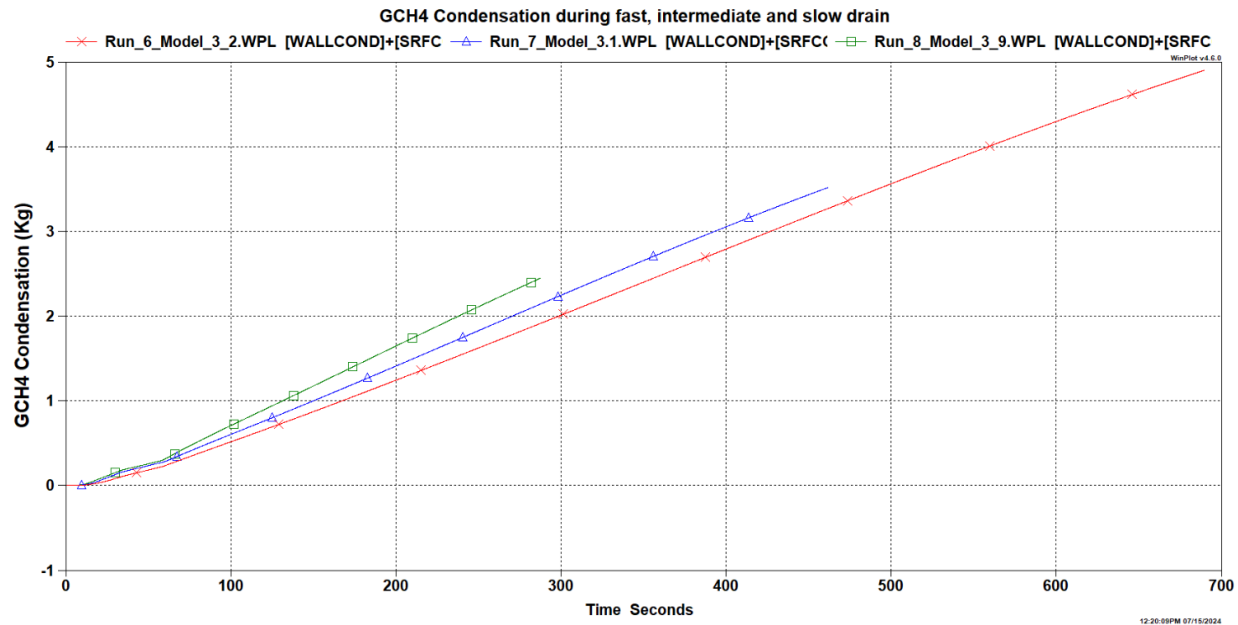


Fig. 23 Predicted condensation (kg) for fast, intermediate, and slow drain

Table 8 shows the comparison of predicted and measured methane consumption for all six cases. Each case was run with the Ring natural convection and Woodfield mixed convection correlations to calculate the heat transfer coefficients. In general, the models with the Ring correlations underpredict methane consumption while those with the Woodfield correlation usually overpredict methane consumption. This is not surprising because the Woodfield correlation calculates higher heat transfer coefficients due to its inclusion of a forced convection component in the correlation. It is observed that predicted consumption matches within 5% for the slow draining rate using either correlation. The mean absolute percentage error (MAPE) using the Ring natural convection correlations is 9%. The MAPE using the Woodfield mixed convection correlation is within 6%.

Table 8: Comparison of Predicted and Measured Methane Pressurant Consumption

Run	Inlet Temp (K)	Drain Time (s)	Measured Mass (kg)	Predicted Mass (Ring) (kg)	Error (Ring) %	Predicted Mass (Woodfield) (kg)	Error (Woodfield) %
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

Table 9 shows the comparison of predicted and measured methane condensation for all six cases using the Ring and Woodfield correlations. Discrepancy with the test data ranges from -18% to 34% when using the Ring correlation, with a MAPE of 19%. Employing the Woodfield correlation, the error ranges from -18% to 8%, with a MAPE of 10%.

Table 9: Comparison of Predicted and Measured Methane Condensation

Run	Inlet Temp (K)	Drain Time (s)	Measured Mass (kg)	Predicted Mass (Ring) (kg)	Error (Ring) %	Predicted Mass (Woodfield) (kg)	Error (Woodfield) %
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

For a few selected cases, wall and ullage temperatures were reported at the end of the draining period. Predicted and Measured wall and ullage temperatures for Runs 6, 8, 9 and 11 are shown in Figures 24, 25, 26, and 27, respectively. The Ring correlation predicted wall temperatures with an average MAPE of 3%, slightly better than the Woodfield correlation with an average MAPE of 7%. The average MAPE in ullage temperatures is 10% for both correlations.

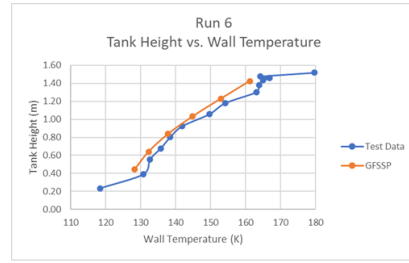
Table 10 provides CPU time and simulation time for six autogenous runs. The CPU time per second of simulation time is also shown in the table. All computations were performed on a PC laptop. CPU time ranges from 15 to 35 seconds depending upon the simulation time. It takes about 0.05 second of CPU time to perform one second of real time simulation.

Table 10: Computational time for all six autogenous runs

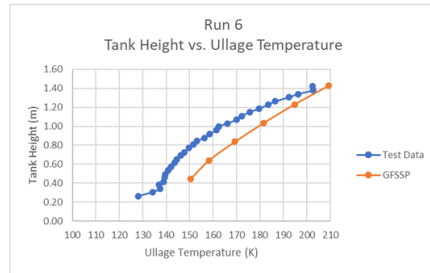
Autogenous Runs	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11
Simulation Time	690	461.8	288.1	694.7	467.4	291
CPU Time	29.38	21.48	15.76	35.09	21.44	15.17
CPU Time/ Simulation Time	0.0425	0.0465	0.0546	0.0505	0.0459	0.0521

Ring Correlation

MAE: 3.18 K
MAPE: 2.2%

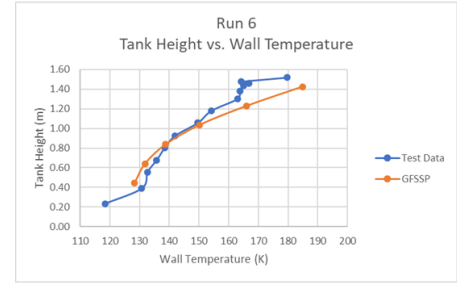


MAE: 12.48 K
MAPE: 7.9%



Woodfield Correlation

MAE: 6.16 K
MAPE: 4.0%



MAE: 6.07 K
MAPE: 4.0%

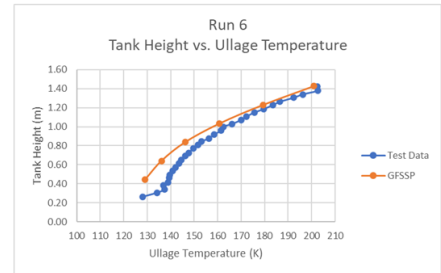
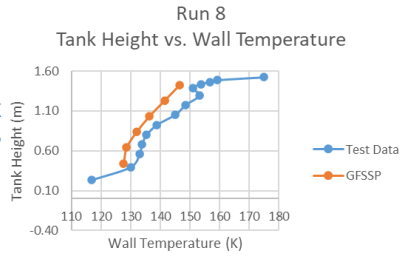


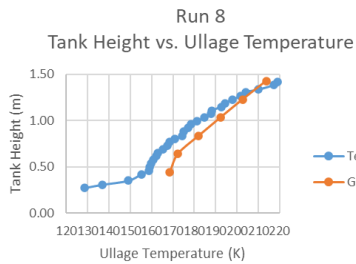
Fig. 24 Predicted and measured wall and ullage temperatures (K) for Run 6 (Slow Drain & Colder Methane)

Ring Correlation

MAE: 6.04 K
MAPE: 4.2%

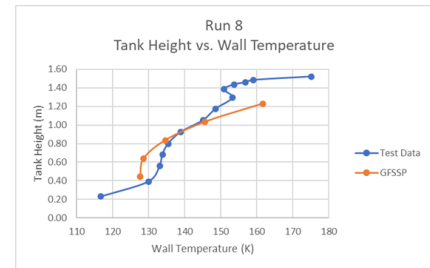


MAE: 7.79 K
MAPE: 4.4%



Woodfield Correlation

MAE: 5.16 K
MAPE: 3.6%



MAE: 23.03K
MAPE: 13.1%

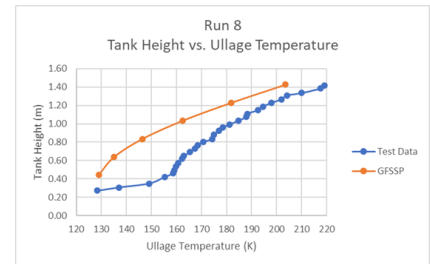
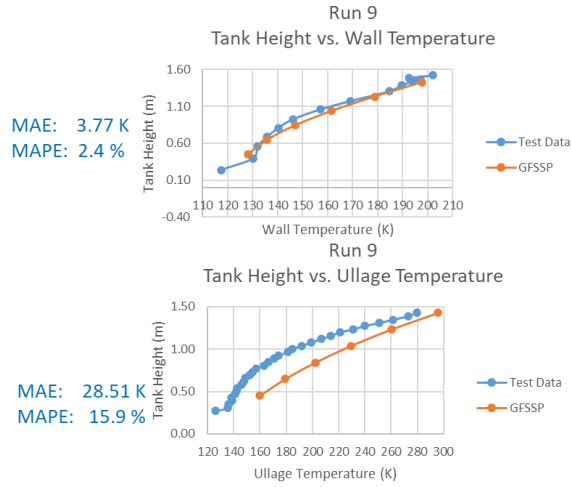


Fig. 25 Predicted and measured wall and ullage temperatures (K) for Run 8 (Fast Drain & Colder Methane)

Ring Correlation



Woodfield Correlation

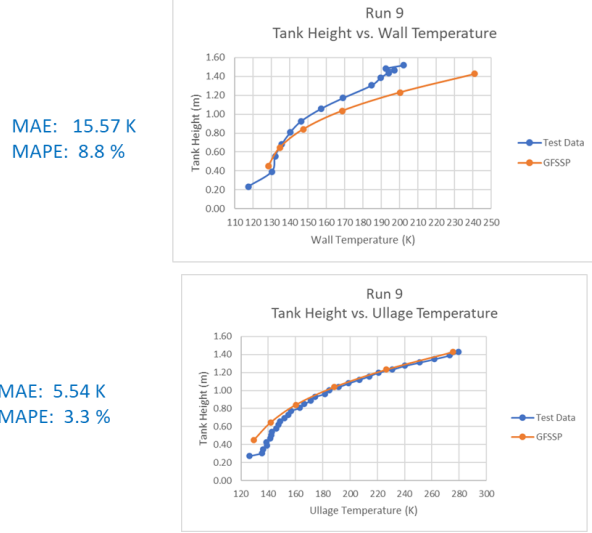
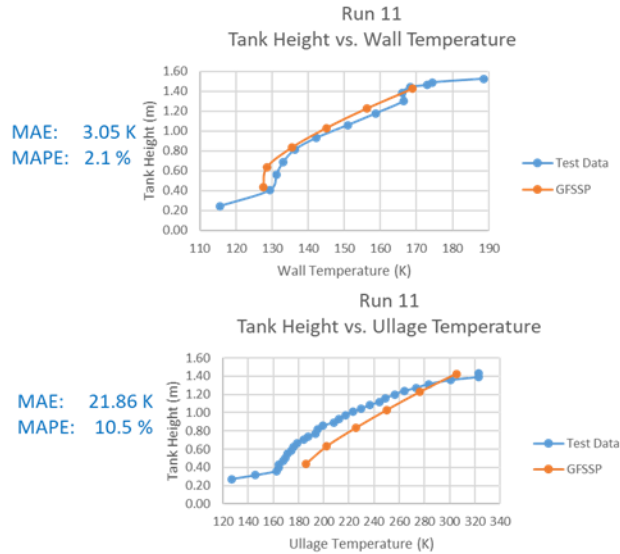


Fig. 26 Predicted and measured wall and ullage temperatures (K) for Run 9 (Slow Drain & Warmer Methane)

Ring Correlation



Woodfield Correlation

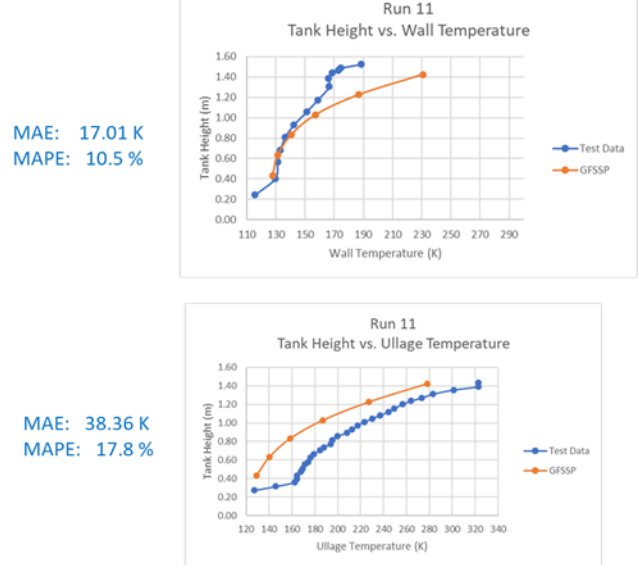


Fig. 27 Predicted and measured wall and ullage temperatures (K) for Run 11 (Fast Drain & Warmer Methane)

VI. Conclusions

This paper presents an improved nodal approach of modeling cryogenic tank pressurization. Unlike conventional tank pressurization models where the ullage is represented by a single fluid node, in this approach the ullage is discretized into multiple fluid nodes, each of which connects with the solid nodes. The volumes of fluid nodes and masses of solid nodes are adapted to expand as the ullage volume grows while the tank drains. A tank pressurization model has also been developed for a single node ullage with multiple solid nodes. Computations have been performed

using both a natural convection correlation and a mixed convection correlation to calculate heat transfer at the wall and liquid-vapor interface. The model also accounts for condensation at the wall and condensation and evaporation at the liquid-vapor interface.

The model results have been compared with the test data of liquid methane tank pressurization using helium and gaseous methane. Twelve test cases were considered where predicted pressurant consumptions were compared with the test data. The mixed convection correlation has been found to be more accurate than the natural convection correlation. Helium consumption compared within -8% to 3% with a mean error of -3%. Positive errors indicate over-prediction and negative indicate under-prediction of the measured data. The MAPE of wall and ullage temperatures are 3 – 6% and 2 – 9% respectively. For a single node ullage with multiple solid nodes, the error in predicted consumption varies from -4 to 4% with a mean error of -0.2%. For autogenous pressurization, the consumption of gaseous methane compared with a MAPE of 9% when using the natural convection correlation and a MAPE of 6% using the mixed convection correlation. The average MAPE values for wall temperatures were 3% and 7% for natural and mixed convection. The average MAPE for ullage temperatures was 10 % for both natural and mixed convection. GFSSP takes about 0.05 second of CPU time to perform one second of real time simulation.

The test data also report the amount of condensation and evaporation of methane in each test. During autogenous pressurization, significant amount of condensation occurs. For helium pressurization, both condensation and evaporation occur; however, the amount of condensation and evaporation is relatively small compared to autogenous pressurization. During the ramp and hold period of helium pressurization, condensation is more predominant because of relatively high methane concentration during this period. However, during draining evaporation occurs at the liquid-vapor interface because of the low partial pressure of methane. The model predicts this phenomenon correctly. However, the percentage error for condensation is quite large in comparison to the autogenous pressurization test cases. A possible reason for the larger percentage discrepancy mass transfer during helium pressurization is the smaller value of condensation. The amount of condensation in autogenous pressurization is almost 30 times larger than condensation or evaporation during helium pressurization. Nevertheless, there is room for further development of the condensation model, and there is also a need for more experimental data with reported uncertainty levels for developing a more accurate condensation model.

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