

Cryogenic Propellant Tank Drain Simulation with a Stratified Ullage Nodal Model

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Cryogenic propellant tank pressurization systems maintain tank pressure within specified limits to comply with propellant thermodynamic and tank structural design requirements [1]. Many pumped cryogenic liquid propulsion systems control tank pressure using an autogenous pressurization system. Autogenous pressurization systems vaporize and heat propellant to produce the pressurant gas delivered to the tank. While autogenous pressurization systems eliminate the need for a separate pressurant gas storage and delivery system, they couple pressurant mass requirements to propellant mass requirements. Accurate prediction of autogenous pressurant mass during propellant drain is essential in optimizing cryogenic propellant tank designs.

The accuracy of predictive models that simulate pressurization during propellant drain was evaluated by comparison to experimental data. Spherical, cryogenic propellant tanks with diameters of 1.52-meter [2] and 3.96-meter [3] were exposed to simulated space environments in a 7.61-meter diameter vacuum chamber at the NASA Lewis Research Center K-site facility [4]. A photograph of the vacuum chamber with the 3.96-meter diameter propellant tank installed is shown on the left and a schematic of the test configuration is shown on the right of Figure 1. This configuration simulates liquid hydrogen (LH2) tank drain with autogenous pressurization and enables independent control of pressurant inlet temperature, ullage pressure, and liquid outflow rate.

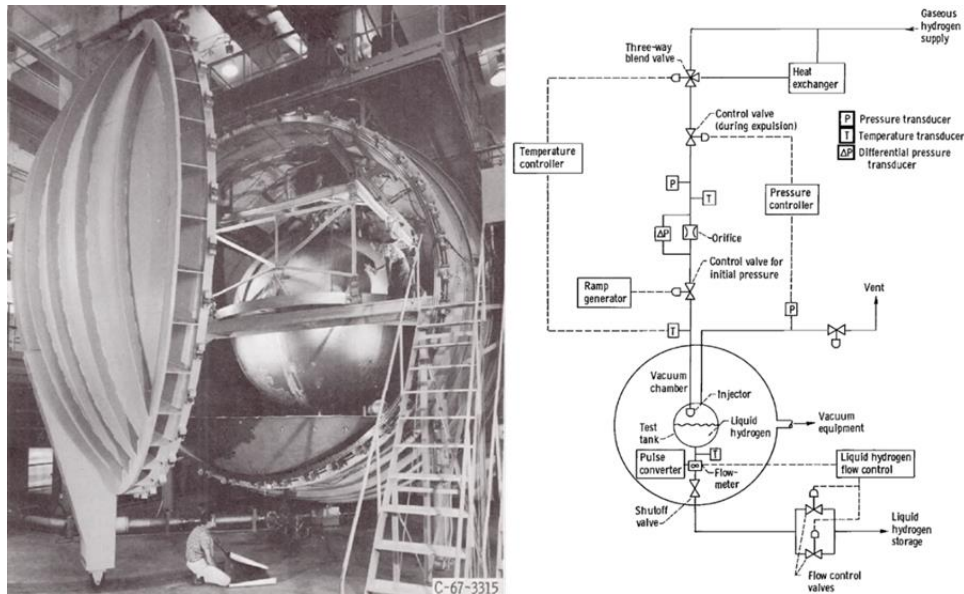


Figure 1. K-site Vacuum Chamber with Test Tank (Left) and Schematic (Right)

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The K-site test procedure begins with LH2 fill to approximately the 98% volumetric fill level and vented replenish until the tank and facility support equipment reach steady state. Pressurization gas thermal conditioning is achieved during tank replenish by flowing gaseous hydrogen (GH2) through the heat exchanger to achieve the specified temperature. After the tank and pressurization gas conditions have reached steady state, LH2 is added or drained as needed to achieve an approximately 95% initial fill level. The ramp phase of testing begins when the tank vent is closed and heated GH2 flows through the injector into the tank to achieve the specified operating pressure in the specified duration. The hold phase of testing begins when the tank initially reaches operating pressure and GH2 is added as needed to maintain a constant tank pressure for the specified duration. The drain phase of testing immediately follows the hold phase and the liquid level decreases from 95% to 5% while maintaining constant tank pressure over the specified duration.

The current investigation uses the Generalized Fluid System Simulation Program (GFSSP), a NASA-developed network flow solver in which a fluid system is discretized into nodes connected by branches, a structural system is discretized into solid nodes connected by solid conductors, and conjugate heat transfer with fluid flow is simulated with convection conductors between fluid and solid nodes [5]. Mass and energy are conserved in fluid nodes to calculate pressure and enthalpy, from which temperature is derived. Momentum is conserved in the branches to calculate flow rates. Energy is conserved in solid nodes and conductors to calculate wall temperatures. Custom logic developed in Fortran language user subroutines enables use of empirical convection coefficient correlations and heat and mass transfer processes such as condensation.

An adaptive multi-node, stratified ullage model was developed using GFSSP. This nodal model represents the ullage volume and corresponding tank wall structure of the propellant tank with multiple fluid and tank solid nodes, which expand uniformly as the liquid propellant drains and the ullage volume and corresponding tank surface area expands. An existing stratified ullage model [6] was modified to represent the ullage with 5, 10, and 20 fluid and solid nodes to investigate sensitivity to stratification model resolution. An annotated schematic of the 5-node stratified ullage model is shown in Figure 2. Higher resolution ullage models differ only in the number of fluid and tank wall nodes and associated branches and conductors.

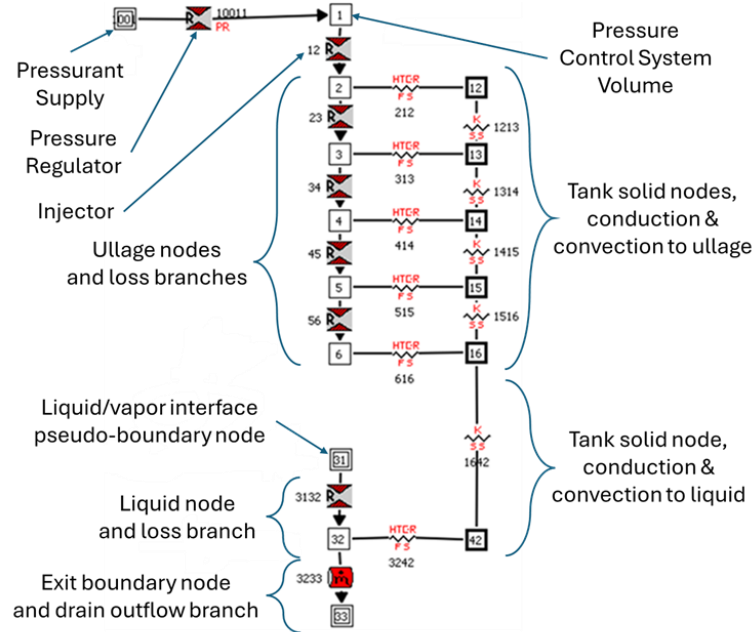


Figure 2. Schematic of 5-node Stratified Ullage GFSSP Model

The initial ullage gas is assumed to be isothermal with an average temperature calculated from reported ullage pressure, reported volumetric ullage fraction, and reported ullage mass prior to tank pressurization during the ramp phase. The initial tank wall temperature is also assumed to be isothermal and the same as the initial ullage temperature. The initial bulk liquid and corresponding

tank wall were both assumed to be in equilibrium with saturation conditions at the initial ullage pressure. The convection environment between the ullage and tank wall is calculated using the mixed convection correlation of Woodfield, et. al. [7]. When the tank wall temperature is greater than the ullage gas saturation temperature, the mixed convection coefficient represents heat transfer from the superheated ullage gas to the tank wall. When the tank wall temperature is less than the ullage gas saturation temperature, the mixed convection coefficient represents heat transfer from the superheated ullage gas to the saturated interface of the condensate film. A condensate film convection environment is calculated using the correlation of Dhir and Lienhard [8] to represent heat transfer from the saturated interface of the condensate film to the subcooled tank wall. The convection environments between the ullage and liquid propellant interface and between the liquid propellant interface and bulk liquid are calculated using the horizontal surface natural convection correlation of McAdams [9]. The condensation rate of ullage gas to a subcooled tank wall and bulk liquid is calculated from a sensible and latent thermal energy balance by assuming equilibrium at the liquid/vapor interphase [10].

Analysis results were compared to test measurements to define model accuracy and sensitivity. Pressurant mass added during drain and local ullage gas and wall temperature were selected as figures of merit. Absolute Percent Error (APE) is defined as the ratio of the magnitude of difference between predicted and measured values to the measured value. Results from multiple test conditions were evaluated using a Mean Absolute Percent Error (MAPE), which is defined as the arithmetic mean of individual APE values. Local temperature results are presented as Mean Absolute Error (MAE), which is defined as the arithmetic mean of the magnitude of difference between predicted and measured temperature. All temperature results were assessed as absolute temperature in the international system of units, i.e. Kelvin.

Predicted pressurant mass APE during drain of the 1.52-meter and 3.96-meter diameter tanks are shown on the left and right, respectively, of Figure 3. These results are presented as a function of drain duration and the number of nodes used to represent the ullage volume in the tank. Increasing model resolution for the smaller tank increases pressurant mass error with larger increases observed for shorter drain durations. Increasing resolution for the larger tank decreases error with minimum error observed for longer drain durations. This behavior demonstrates the existence of an optimum ullage model resolution that minimizes pressurant mass error.

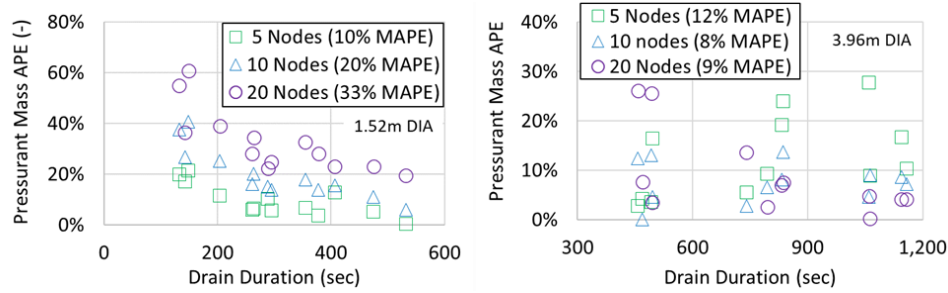


Figure 3. Pressurant Mass Error Sensitivity to Model Discretization

Predicted fluid and tank wall temperatures at the end of drain are shown on the left and right, respectively, of Figure 4. Results for the 1.52-meter diameter tank are presented at the top while those for the 3.96-meter diameter tank are presented at the bottom. Increasing stratified model resolution improves accuracy of fluid and wall temperatures near the forward end of the tank. The 1.52-meter diameter tank results demonstrate as much as a 6 K decrease in the MAE of the fluid temperature, but only a 1 K decrease in the MAE of the tank wall temperature as ullage model resolution increases. The 3.96-meter diameter tank results demonstrate as much as a 20 K decrease in the fluid temperature, but as much as a 9 K increase in MAE of the tank wall temperature as ullage model resolution increases. This behavior demonstrates the existence of an optimum ullage model resolution that minimizes temperature error.

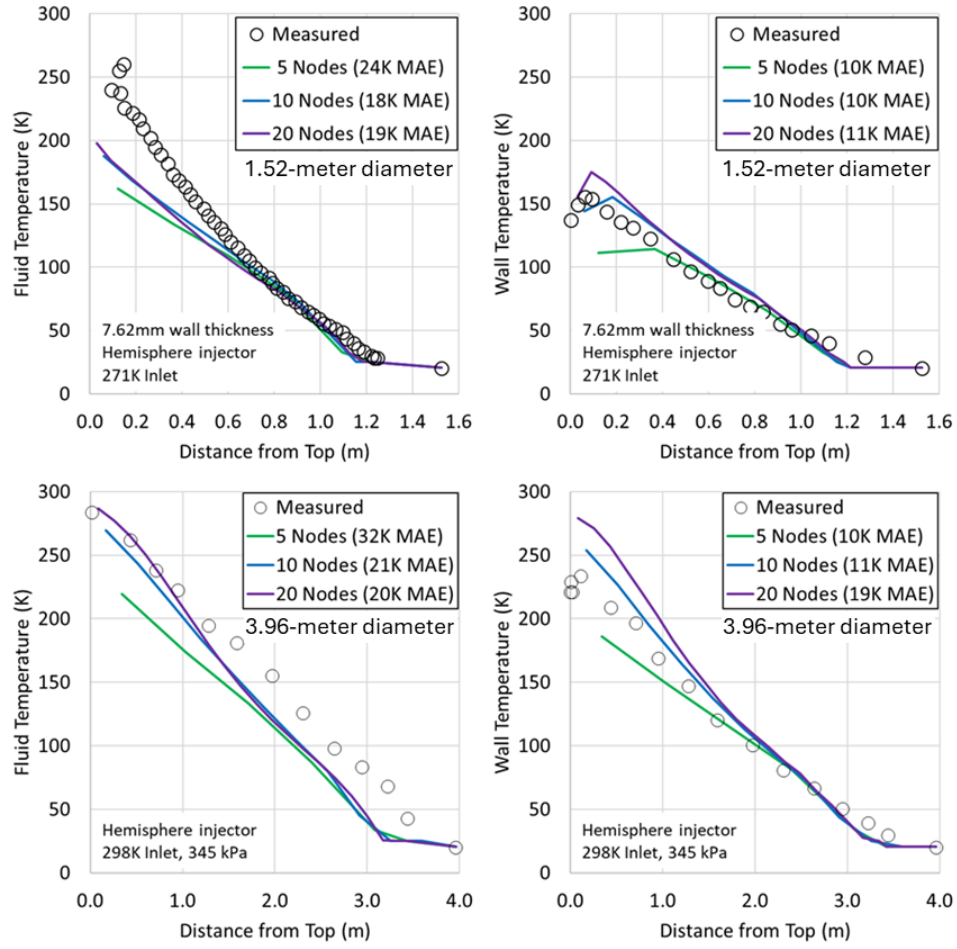


Figure 4. Fluid and Tank Wall Sensitivity to Model Resolution

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