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Nodal Modeling of Liquid Propellant Feed and Pressurization System

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Abstract

Nodal or network flow modeling plays an important role in the design and operation of the feed and pressurization system of a liquid rocket engine. Model development and execution time is relatively short for nodal codes in comparison to the Navier-Stokes based CFD codes. Nodal models also allow the inclusion of several components into one model to predict the behavior of a larger system. Unlike CFD models, the nodal models do not need very fine discretization of the flow field because they use empirical correlations to model fluid friction and heat transfer. This paper presents several applications of nodal modeling of liquid propellant feed and pressurization systems using the Generalized Fluid System Simulation Program (GFSSP), a nodal code developed at NASA/ Marshall Space Flight Center. GFSSP discretizes the flow field into nodes which are connected by branches. The mass and energy conservation equations and the equation of state are solved to calculate pressure, temperature, and resident mass at the nodes. The momentum equations are solved at the branches to calculate flow rates. Applications include a) tank pressurization by inert gas as well as autogenous pressurization by gaseous propellant, b) submerged pressurization by helium, c) self-pressurization due to boil-off of cryogenic propellant, d) chilldown of a transfer line of a cryogenic propellant feed system, and e) chilldown and filling of a cryogenic tank. Each of the above-mentioned models was verified and validated by comparing with test data.

1. Introduction

The analysts and designers of liquid propellant feed and pressurization systems often need to know pressures, temperatures, flowrates, concentrations, and heat transfer rates at different parts of a flow circuit for steady state or transient conditions. Such applications occur in propulsion systems for tank pressurization, internal flow analysis of rocket engine turbo-pumps, chilldown of cryogenic tanks and transfer lines and many other applications of gas-liquid systems involving fluid transients and conjugate heat and mass transfer. Computer resource requirements to perform time-dependent three-dimensional Navier-Stokes Computational Fluid Dynamic (CFD) analysis of such systems are prohibitive and therefore are not practical. A possible recourse is to construct a fluid network consisting of a group of flow branches such as pipes, valves and various flow control devices that are joined together at a number of nodes. They can range from simple systems consisting of a few nodes and branches to very complex networks containing many flow branches simulating valves, orifices, bends, pumps and turbines. In the analysis of existing or proposed networks, node pressures, temperatures and concentrations at the system boundaries are usually known. The problem is to determine all internal nodal pressures, temperatures, concentrations, and branch flow rates. Such schemes are known as Nodal Flow Analysis methods, and they use largely empirical information to model fluid friction and heat transfer.

The purpose of this paper is to introduce Generalized Fluid System Simulation Program (GFSSP) [1], a nodal network flow analysis code, developed at NASA Marshall Space Flight Center and describe several Liquid Propulsion System Analysis applications using GFSSP, namely Tank Pressurization, Chilldown of Cryogenic Transfer Line and Filling of Cryogenic Tank.

2. Introduction to GFSSP

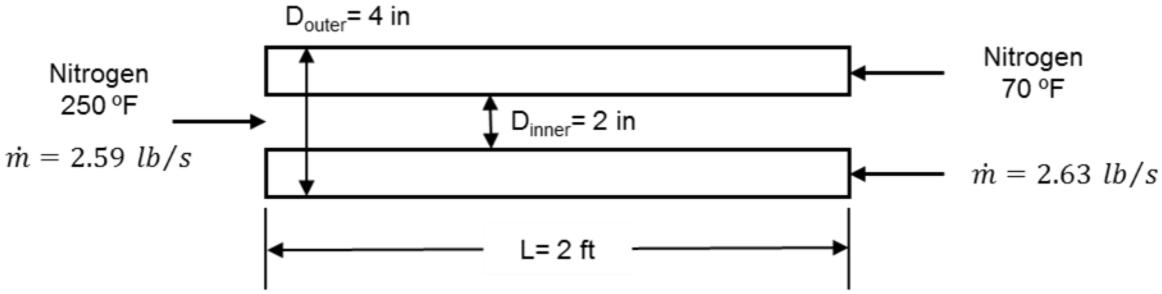
GFSSP has been developed to perform nodal analysis of Liquid Propulsion Systems. GFSSP discretizes a flow system into nodes and branches. The nodes are interconnected by branches. The pressures and temperatures are computed at the nodes whereas the flowrates are computed at the branches. A pressure based finite volume formulation is used to solve mass, momentum, and energy conservation equations in conjunction with thermodynamic equation of state to calculate pressure, flowrate, and resident mass in the node. These equations are solved simultaneously by the Newton-Raphson (N-R) iterative method. The energy equation is decoupled from the thermo-hydraulic equations by solving outside of the N-R loop, and thermodynamic properties are evaluated from computed pressure and enthalpy.

Solid nodes are added to the flow circuit when solid to fluid heat transfer is critical (i.e., Conjugate Heat Transfer). In addition to solving energy conservation equation for fluid, GFSSP also solves for energy equation of solid, and the two separate equations communicate with each other through a source term which calculates solid to fluid heat transfer.

GFSSP has a graphical user interface, MIG (Modeling Interface for GFSSP), which uses the paradigm of ‘point and click’ to construct the flow circuit consisting of nodes, branches, and conductors, supply geometrical property, and initial and boundary conditions. GFSSP uses a plotting software, WINPLOT, developed at NASA/Marshall Space Flight Center to display results of unsteady simulation.

2.1 Network Definition

Figure 1 shows a GFSSP model of a counterflow heat exchanger. The annular section carries cold gas and hotter fluid flows through the inner tube. Nodes 1 through 7 represent the inner tube and nodes 18 through 24 represent the annular tube. These two independent flow circuits are connected by solid nodes 8 through17. It may be noted that there are two kinds of fluid node: Boundary Node and Internal Node. Pressure and temperatures are specified at Boundary Nodes and pressures and temperatures are computed at Internal Nodes. Typically, flowrates are not specified at the inlet. Flowrates are calculated by solving momentum equations which account for pressure differential, flow resistances and external forces such as gravity.



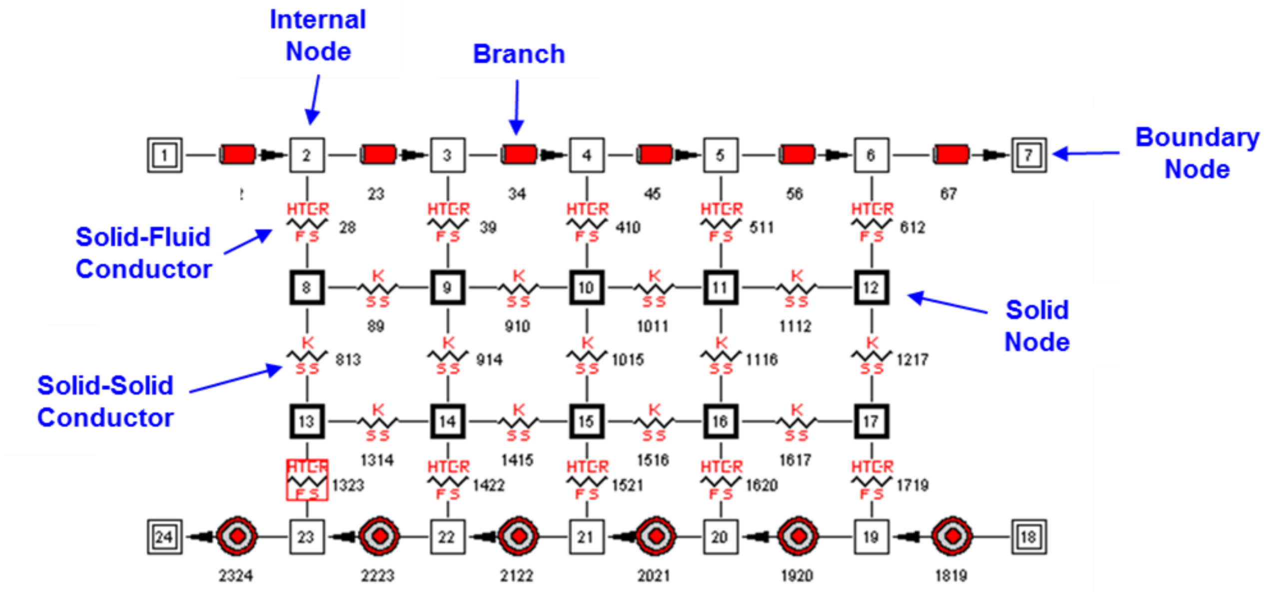


Figure 1. GFSSP flow network for a counterflow heat exchanger

This is also a conjugate heat transfer model where heat is transferred from hot side (annular space) to cold side (inner tube) through solid nodes. Both conduction and convection heat transfer are accounted for by solid-to-solid and solid-to-fluid conductors.

2.2 Program Structure

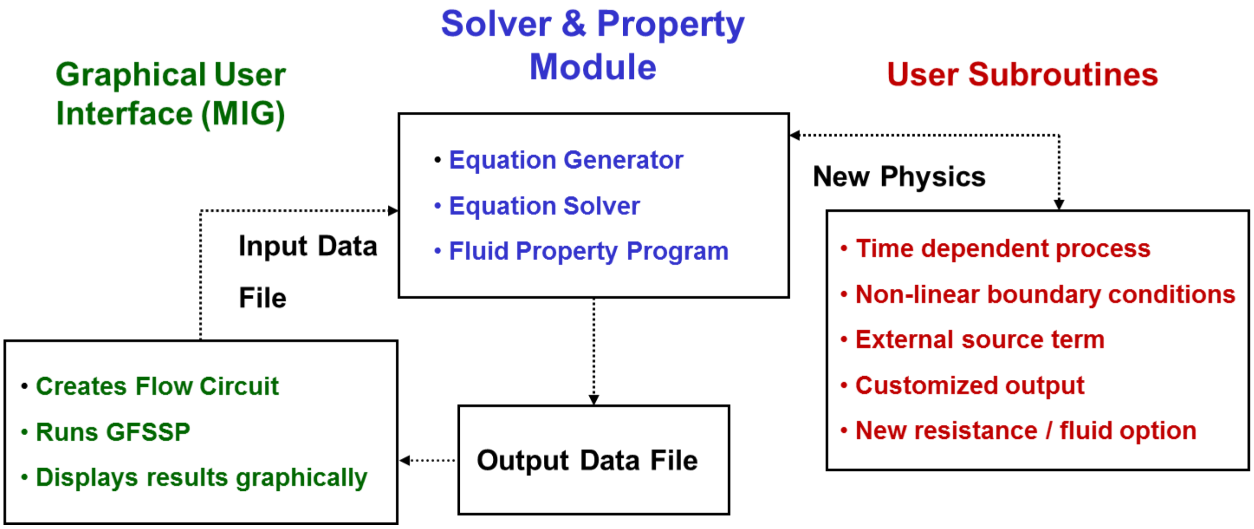


Figure 2. GFSSP Program Structure

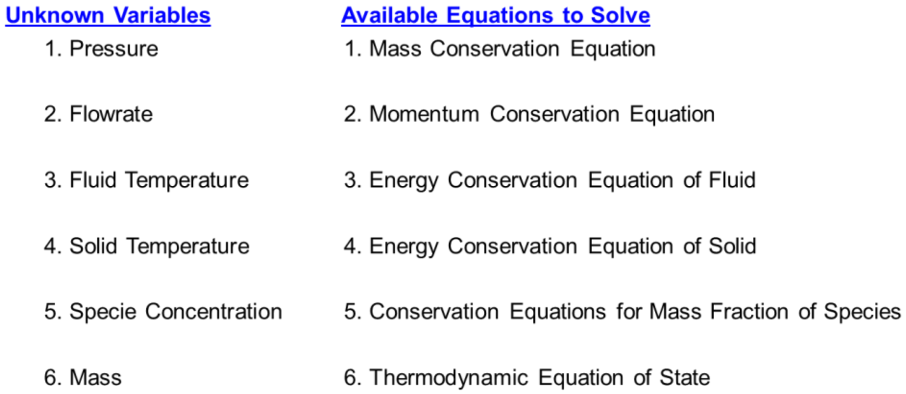
Figure 2 shows the program structure. GFSSP consists of three modules. The graphical user interface, MIG, provides a visual platform to build the model and create an input data file that is read by the solver module which generates all necessary equations with the help of built-in-thermodynamic property programs, solves the equations and provides the output. The User Subroutines module consist of several blank subroutines called from the solver module. The User Subroutines module gives the opportunity to the advanced users to incorporate new physics to the model. This could include any time dependent process, non-linear boundary conditions, external source terms, customized output and new resistance or fluid option.

2.3 Mathematical Formulation

The governing equations to compute primary variables such as pressure and flowrates are listed in Table 1. It may be noted that pressure is computed from the mass conservation equation indicating that GFSSP uses a pressure-based scheme. GFSSP uses a combination of simultaneous and successive substitution schemes to solve the equations listed in Table 1. Mass conservation, momentum conservation and equation of state are solved by simultaneous Newton-Raphson method whereas the remaining equations in the table are solved outside the simultaneous N-R loop primarily using a successive substitution scheme.

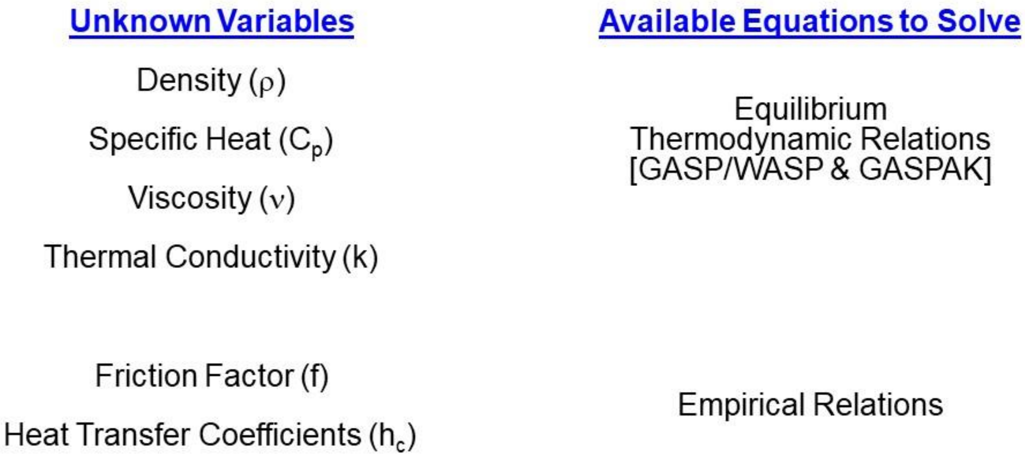
In addition to primary variables, auxiliary variables such as density, viscosity and friction factor are computed from thermodynamic property program and empirical relations. The list of auxiliary variables needed are shown in Table 2. Thermodynamic and thermo-physical properties such as density, specific heat, viscosity and thermal conductivity are evaluated from thermodynamic property programs, GASP [2] or GASPAK [3]. Friction factor and heat transfer coefficients are evaluated from empirical correlations.

Table 1. Mathematical Closure for solving primary variables



Unknown Variables	Available Equations to Solve
1. Pressure	1. Mass Conservation Equation
2. Flowrate	2. Momentum Conservation Equation
3. Fluid Temperature	3. Energy Conservation Equation of Fluid
4. Solid Temperature	4. Energy Conservation Equation of Solid
5. Specie Concentration	5. Conservation Equations for Mass Fraction of Species
6. Mass	6. Thermodynamic Equation of State

Table 2. Secondary Variables needed to solve the governing equations



Unknown Variables	Available Equations to Solve
Density (ρ)	Equilibrium Thermodynamic Relations [GASP/WASP & GASPAK]
Specific Heat (C_p)	
Viscosity (ν)	
Thermal Conductivity (k)	
Friction Factor (f)	Empirical Relations
Heat Transfer Coefficients (h_c)	

3. GFSSP Applications in Liquid Propulsion System

3.1 Tank Pressurization

Direct Pressurant Injection

The purpose of the cryogenic propellant tank pressurization system is to control the pressure in the gas space of the tank (known as the ullage space) and the propellant mass flow rate to the engine. A mathematical model is required to predict the ullage and propellant conditions to ensure that pressure and temperature levels inside the tank remain within acceptable limits. The other purpose of the mathematical model is to estimate the requirement of pressurant to maintain the desired tank pressure. The pressurant gas could be helium or gaseous propellant (known as autogenous pressurization). The pressurant gas can either be injected into ullage or in the liquid (known as submerged pressurization).

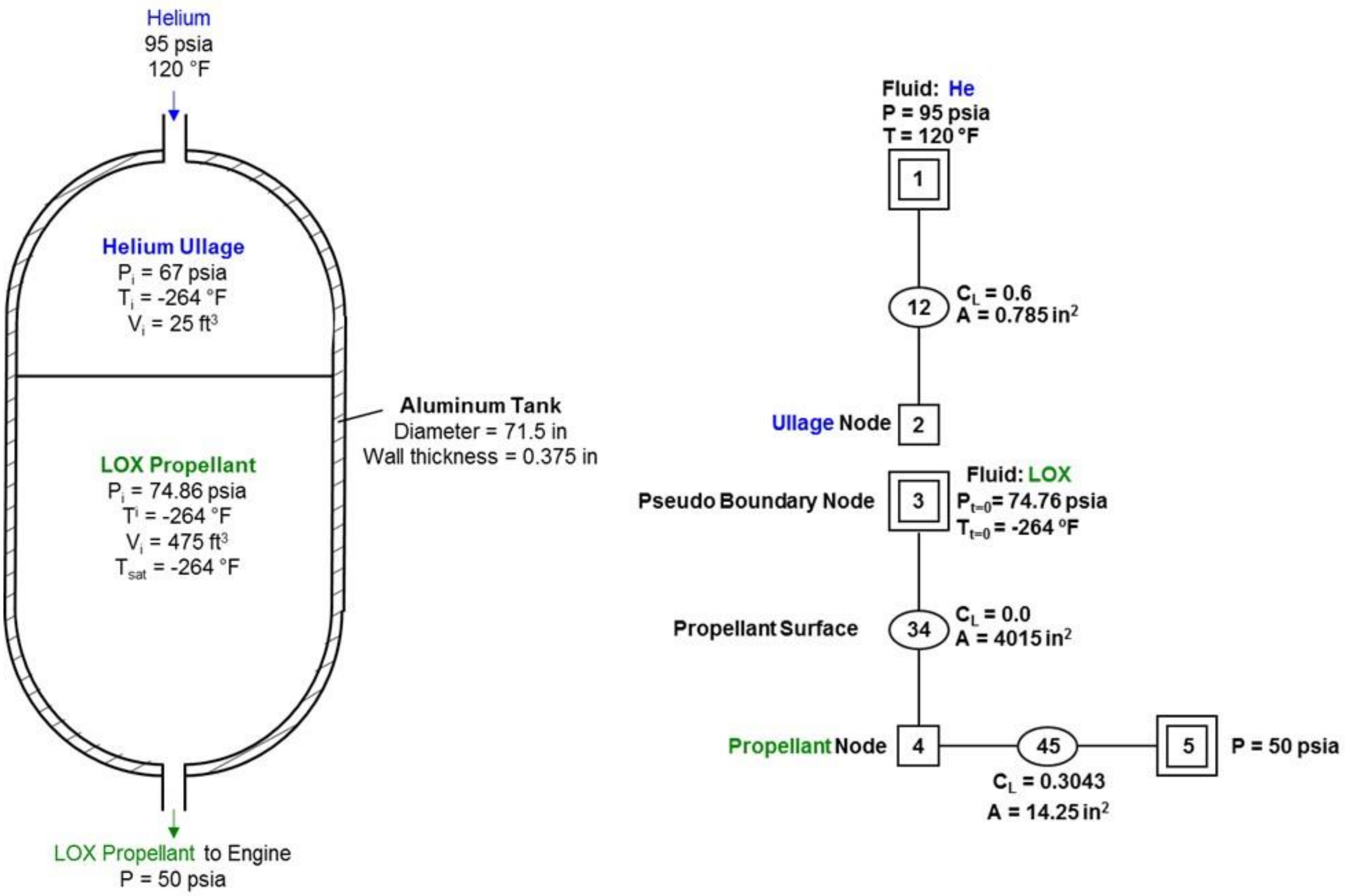


Figure 3. Schematic and GFSSP model of propellant tank pressurization system

A simple GFSSP model [4] with one node representing ullage and one node representing propellant has been developed (Figure 3). Volumes of both ullage and propellant nodes vary as the tank drains. Heat and mass transfer between ullage and liquid and heat transfer between ullage and tank wall were accounted for by assuming the heat transfer between ullage and propellant and between ullage and tank wall were due to natural convection. The predicted helium consumption was compared with the Epstein correlation [5] and model results compared within 3%.

This pressurization model was further extended to include a control valve and was used to model helium pressurization system of propulsion test article (PTA) at NASA/Stennis Space Center [6]. PTA consists of LOX and RP-1 tanks with a total usable propellant load of 44,000 lbm. A schematic of the PTA pressurization system is shown in Figure 4. This system consists of a LOX tank and an RP-1 tank that are both pressurized by helium. A GFSSP model (Figure 5) was developed to predict the ullage and propellant conditions during priming and engine firing. The predicted pressure distribution compares well with test data as shown in Figure 6. It may be noted that the predicted frequencies of closing and opening the valve are in good agreement with measurements both prior to engine start and during engine firing.

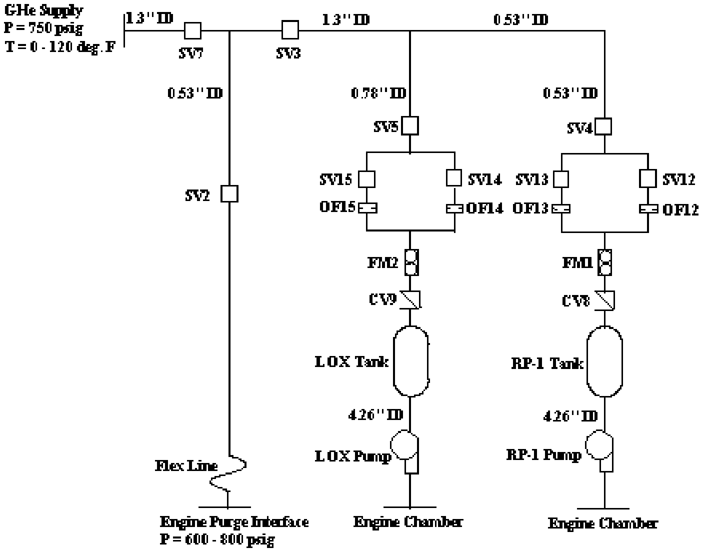


Figure 4. Helium pressurization system of PTA

Submerged Pressurant Injection

Subcooling of cryogenic propellant by helium injection is one of the most effective methods for suppressing bulk boiling and keeping propellant in a subcooled condition for pre-launch. For tank pressurization, submerged helium injection can substantially reduce helium consumption by infusing gaseous propellant into the tank ullage. A GFSSP model [7] of the helium bubbling process in liquid oxygen has been developed. The purpose of the model was to calculate the amount of subcooling of liquid oxygen due to evaporative heat and mass transfer. The numerical model developed with GFSSP has been validated against two sets of experimental data [8,9] and has been shown to predict both propellant subcooling and helium consumption within 30%.

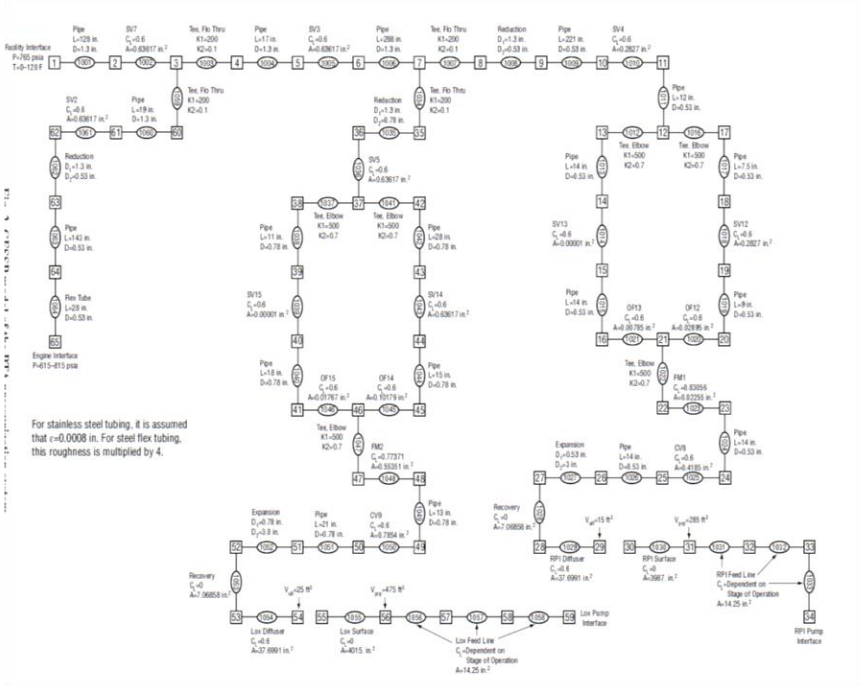


Figure 5. GFSSP Model of the PTA Pressurization System

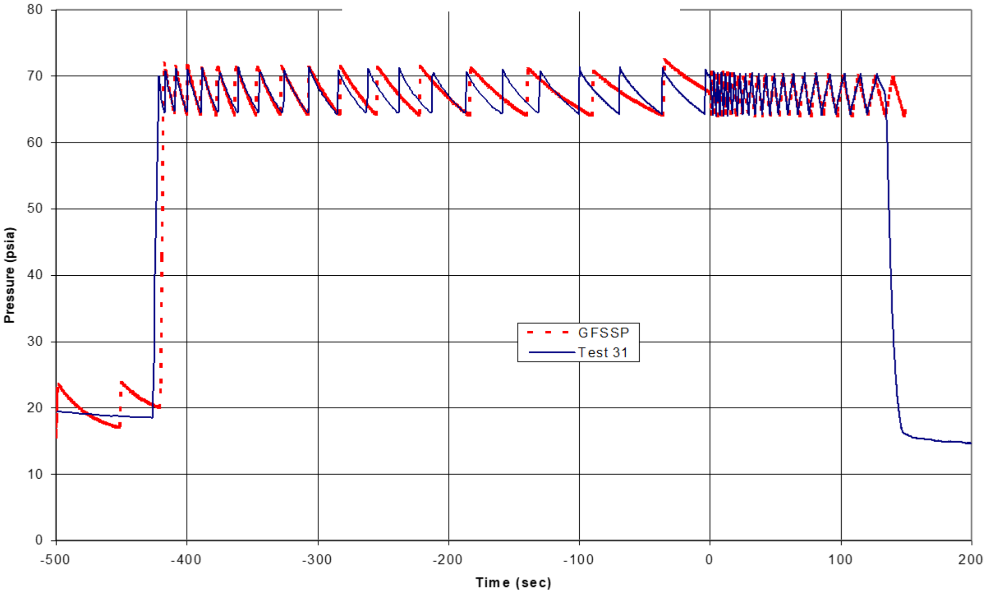


Figure 6. Comparison between LOX tank ullage pressure prediction and test data.

Self-Pressurization

In space, cryogenic tanks get pressurized due to boil-off caused by external heat load. To control the pressure, the tank must be vented, and precious propellant is lost in space. To minimize propellant loss, the pressure in the tank is controlled by injecting a small amount of cold propellant into the ullage. The propellant is cooled by a thermodynamic vent system (TVS) consisting of a Joule-Thomson (J-T) valve and a heat exchanger as shown in Figure 7. A small amount of propellant is pumped, and a smaller portion is sent though a J-T valve for producing a colder mixture of liquid and vapor.

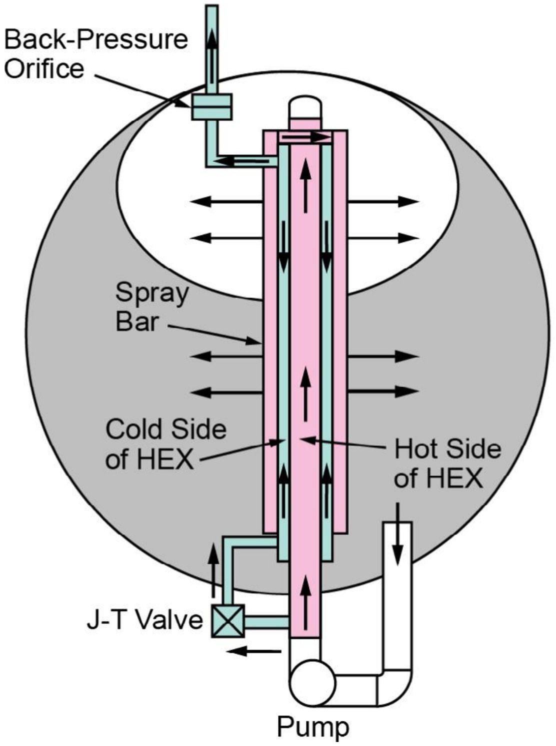


Figure 7. Schematic of Thermodynamic Vent System

The colder mixture of liquid and vapor is used to cool the rest of liquid drawn by the pump. The colder fluid is injected into ullage to reduce the pressure. TVS is used to keep the tank pressure within a specified band.

A GFSSP model of Self Pressurization of an LH2 Tank with pressure control by a TVS was developed [10]. Multipurpose Hydrogen Test Bed (MHTB) [11] shown in Figure 8 consists of a full-scale flight size tank in a vacuum chamber. The passive thermal control system of the MHTB is composed of a combination of spray-on foam insulation (SOFI) and a multilayer insulation (MLI) system. Figure 9 shows the integrated GFSSP model of LH2 tank and TVS. The tank model provides the boundary condition of TVS, and the TVS model provides flowrate and enthalpy of the spraying propellant. Measured and predicted ullage pressure are shown in Figure 10. A good comparison between prediction and measured data was observed.

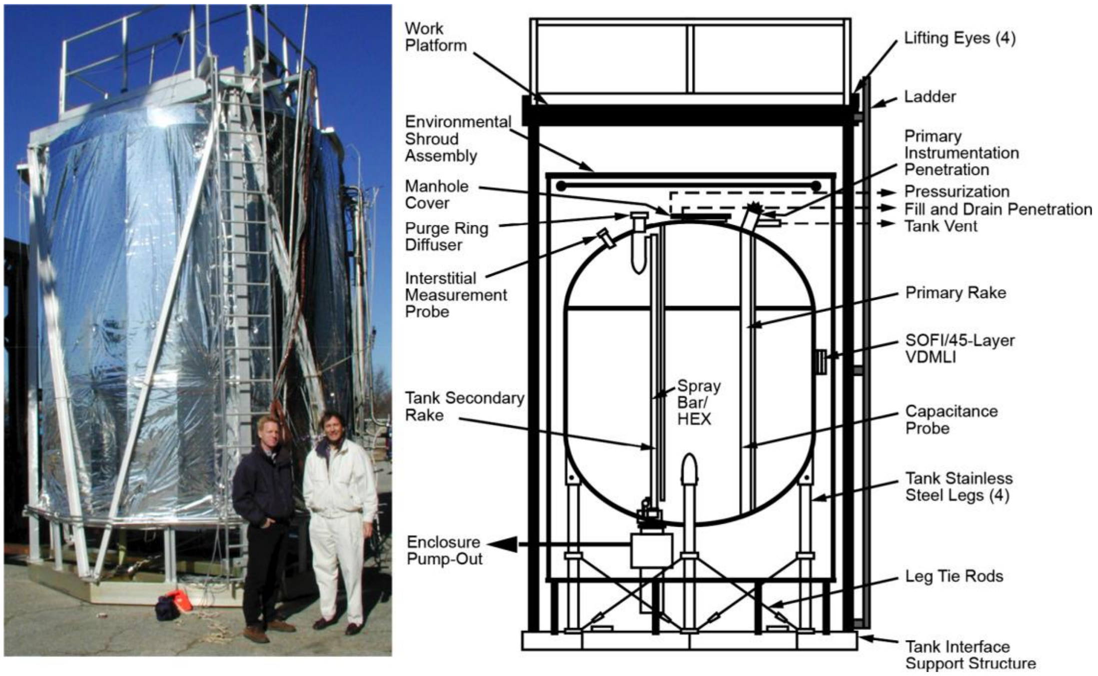


Figure 8. Multipurpose hydrogen Test Bed at NASA/Marshall Space Flight Center [11]

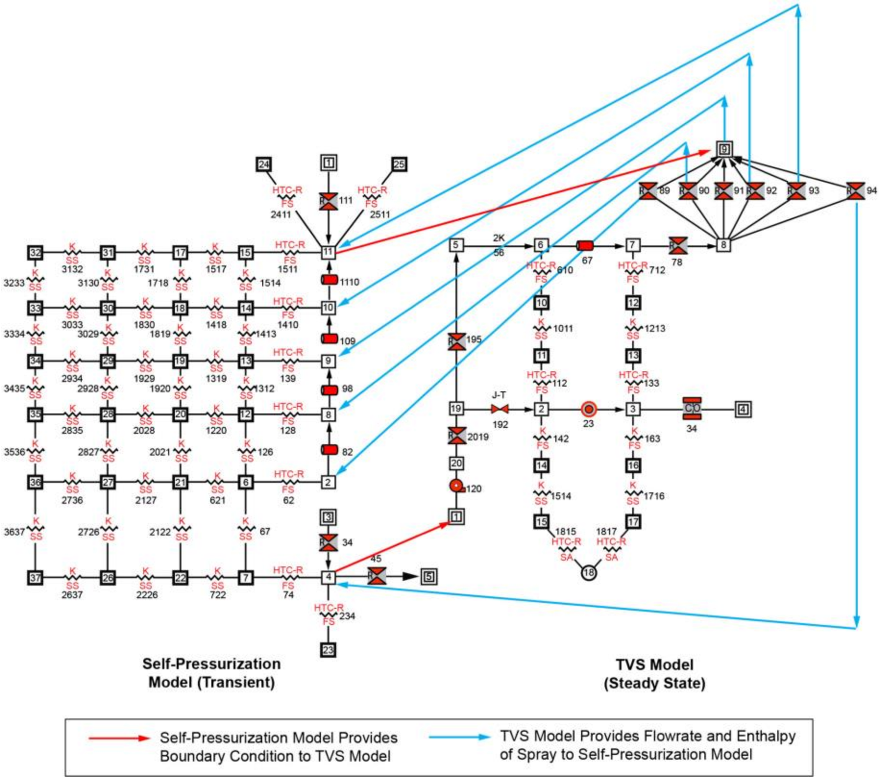


Figure 9. Integrated Self-Pressurization and TVS models.

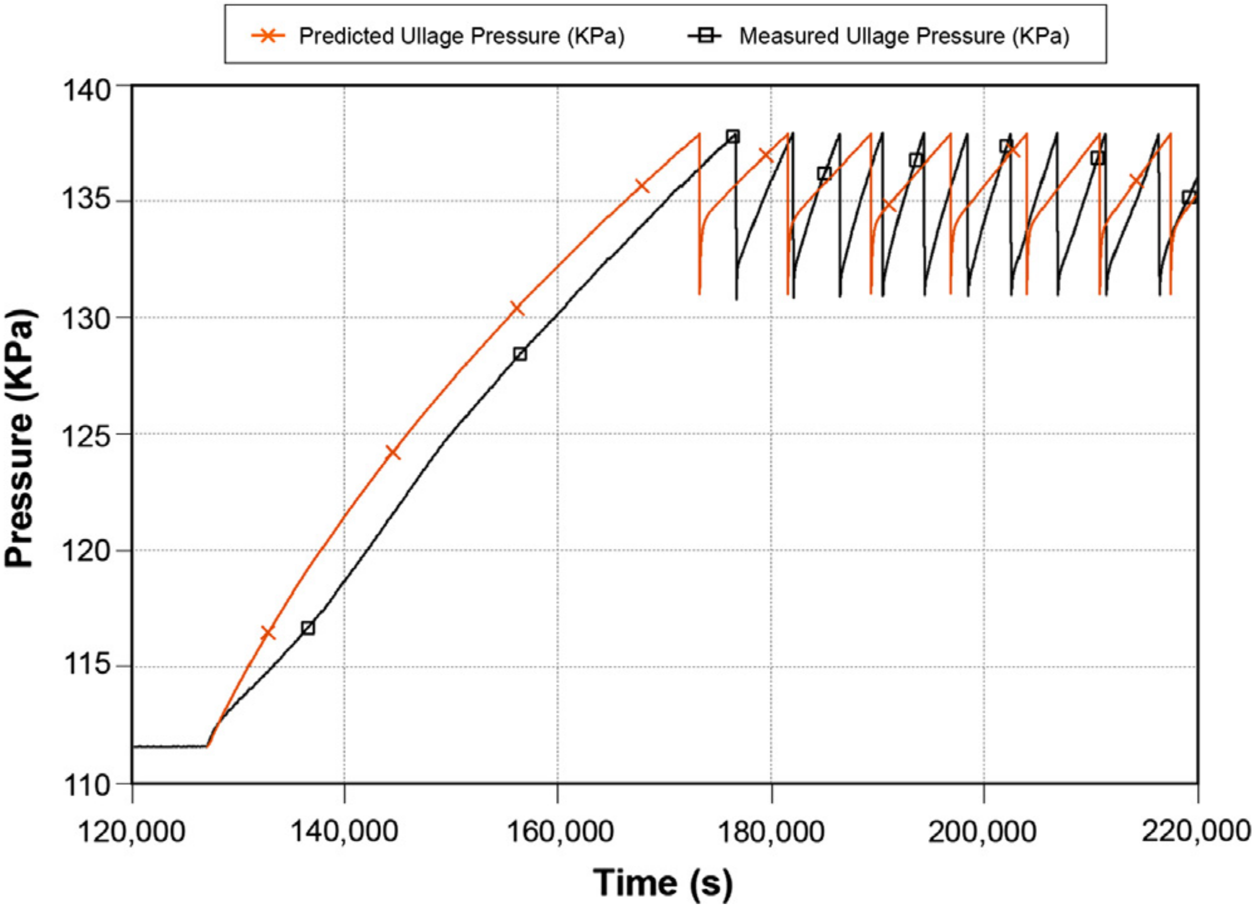


Figure 10. Measured and Predicted ullage pressure with TVS Spray

3.2 Chilldown of Cryogenic Transfer Line

The operation of a cryogenic propulsion system, such as those found in spacecraft and missiles, requires transfer line chilldown before establishing a steady flow of cryogenic fluid between various system components. Cryogenic transfer line chilldown is a transient heat transfer problem that involves rapid heat exchange from a solid surface to a fluid with phase change.

GFSSP's conjugate heat transfer algorithm was validated [12] by comparing with analytical solution of chilldown of a pipe with superheated hydrogen vapor with a constant heat transfer coefficient. GFSSP model with phase change was developed [13] to compare the test data [14] of long transfer line chilldown using liquid nitrogen and hydrogen. Figure 11 shows the test setup of cryogenic transfer line used by National Bureau of Standard (NBS). The GFSSP model of the test setup is shown in Figure 12. The comparison between predicted and measured chilldown time is shown in Table 3. The average discrepancy between measured and predicted data is within 7.63 %.

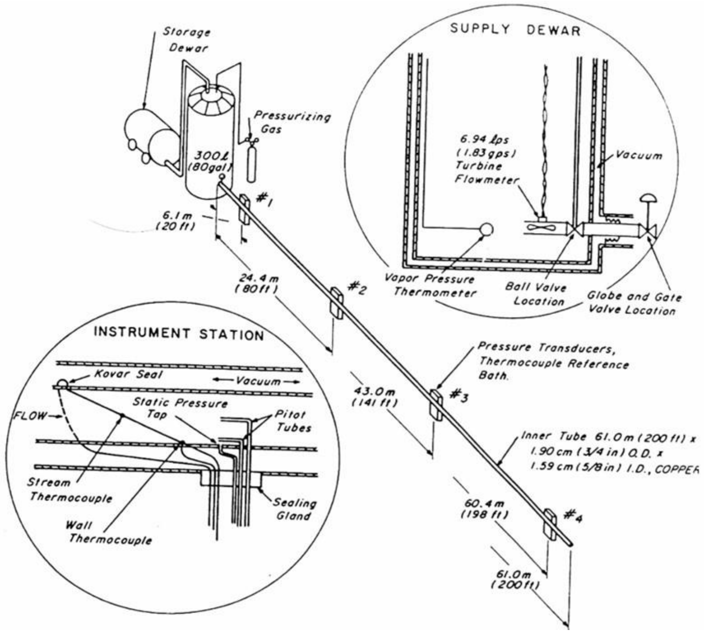


Figure 11. Test Setup of Cryogenic Transfer Line

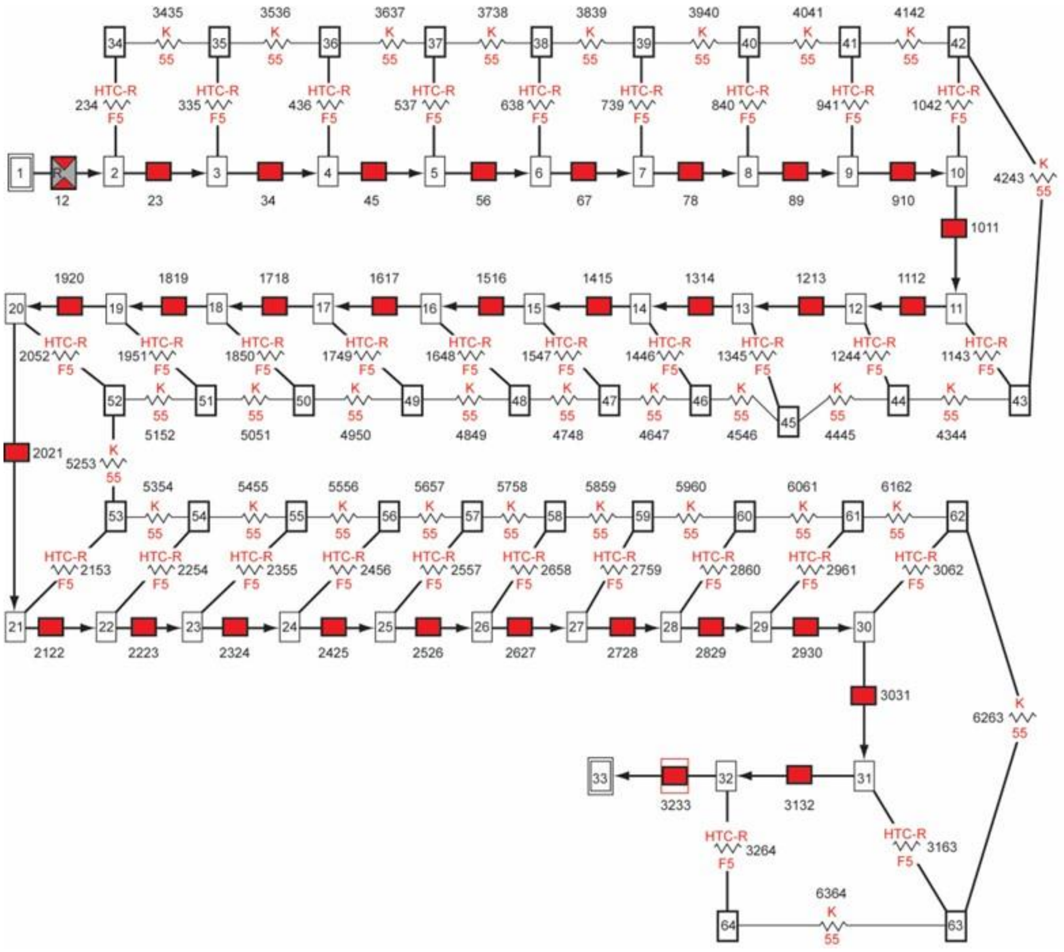


Figure 12. GFSSP Model of Test Setup of Cryogenic Transfer Line

Table 3. Comparison of predicted and measured chilldown time

Saturated LH_2 chilldown time for various driving pressures

Driving Pressure (psia)	Saturation Temperature (°F)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
74.97	−411.06	68	70
86.73	−409.08	62	69
111.72	−406.4	42	50
161.72	−402.13	30	33

Subcooled LH_2 chilldown time for various driving pressures. LH_2 is subcooled at –424.57 ºF

Driving Pressure (psia)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
36.75	148	150
61.74	75	80
86.73	62	60
111.72	41	45
136.72	32	35
161.7	28	30

Saturated LN_2 chilldown time for various driving pressures

Driving Pressure (psia)	Saturation Temperature (°F)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
61.74	−294.09	165	185
74.97	−289.71	150	160
86.73	−286.24	130	140

Subcooled LN_2 chilldown time for various driving pressures. LN_2 is subcooled at –322.87 ºF

Driving Pressure (psia)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
36.75	222	250
49.97	170	175
61.74	129	140
74.97	100	100
86.73	85	90

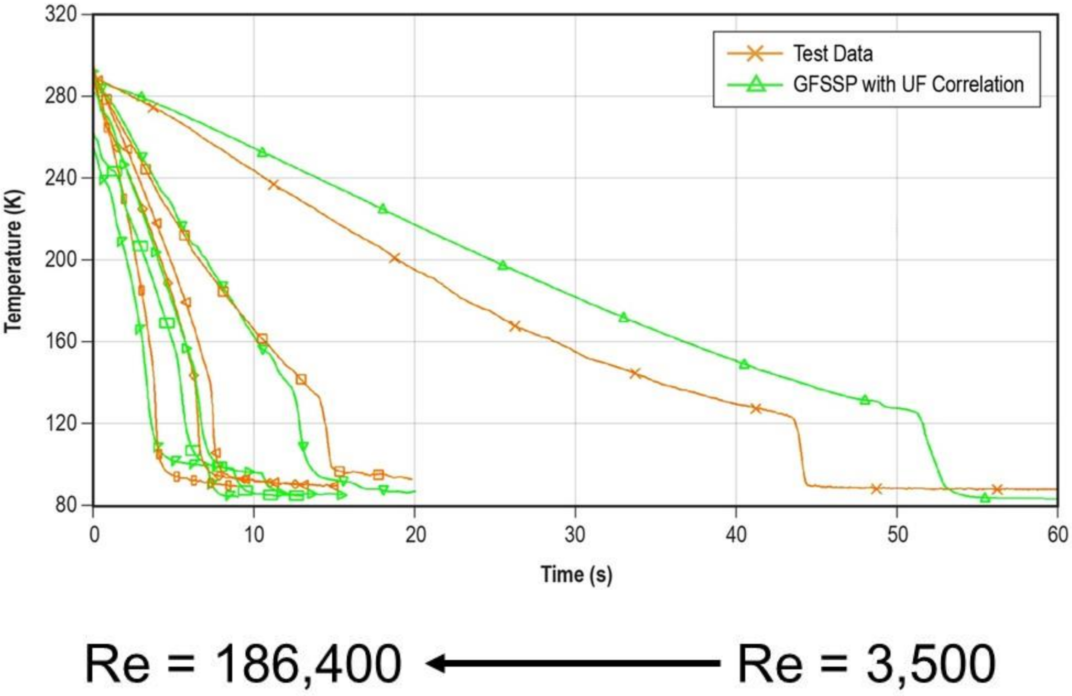


Figure 13 Predicted and measured temperature distribution for 5 cases of horizontal tube using liquid nitrogen

For a shorter tube, University of Florida has developed a new chilldown boiling correlation from a series of cryogenic experiments with liquid nitrogen and hydrogen. This correlation has been coded as a Fortran user subroutine [15]. The model's predicted wall temperatures are compared to test data in Figure 13. The model predicts the transition of film to nucleate boiling and the transition point is predicted reasonably well.

3.3 No Vent Chill and Fill of Cryogenic Tank

Filling a tank with cryogenic fluid is more challenging than filling a tank with water or any other fluid that is in liquid state at atmospheric condition. Filling a tank with cryogenic fluid is a two-step process. First the tank and the transfer line must be chilled. Liquid cryogens start flowing into the tank only after the tank and transfer lines are chilled to the fluid saturation temperature. In normal gravity, cryogenic tanks are usually filled from the bottom at nearly atmospheric pressure. The vapor, caused by heat transfer from the warm tank walls, is allowed to vent from the top of the tank while the tank is being filled. Filling a cryogenic tank in the absence of gravity is more challenging because in a non-stratified environment liquid propellant may not settle at the tank bottom as it does on earth. There is a strong possibility that liquid propellant may exit through the vent valve, which is typically located at the top of the tank to vent propellant vapor. There are several methods of filling a tank in space.

To reduce the loss of precious propellant, a "charge-hold-vent" (CHV) method of tank filling [16] was developed. During the charge period, a small quantity of liquid cryogen is injected into the evacuated tank. Initially, the liquid flashes due to the low tank pressure, and then the remaining liquid droplets evaporate as they contact warm vapor or the tank wall. During the hold period, the circulating flow pattern induced from the spray nozzles provides convective heat transfer from cold vapor to the tank wall. The primary mode of heat transfer during the hold is convection. At the completion of the hold period, the pressure has risen considerably, and the tank is ready to be vented. This cycle of processes is repeated until tank wall is cooled to the saturation temperature. Once the tank wall is cooled, the tank is filled with the vent being closed.

A simpler method is that of Vented-Chill / No-Vent-Fill (VCNVF) [17]. In this method, the tank's vent valve is open for an initial period while the tank walls are chilled with a spray of cryogenic liquid that boils to vapor and exits through the vent. When the tank walls have been sufficiently chilled, the vent valve is closed, and the tank is filled with liquid. Care must be taken with the timing of the vent closure. If the vent is closed too early, residual heat in the walls may drive sufficient boil-off to raise the tank pressure high enough to stall the inlet flow. If the vent is closed too late, some liquid propellant may be lost out the vent. Compared to the CHV method, VCNVF is less mass efficient; the gas being vented during the chill may not be extracting the maximum possible thermal energy from the tank wall. There is always the risk that some of the precious liquid propellant will be vented. However, VCNVF is much simpler from an operational standpoint. The transfer lines need to be chilled down only once and there is less cycling of inlet and vent valves. Since there is no hold period, overall loading time is likely to be shorter.

The limitation of the VCNVF method to find an optimum target temperature was overcome by the No Vent Fill (NVF) method where a TVS (Thermodynamic Vent System) augmented injector was used with the vent valve closed during the entire filling process. NVF tests were conducted in the CRYogenic Orbital Testbed (CRYOTE) tank, which was also used for carrying out the VCNVF test. In a TVS-augmented injector, the liquid flow splits into two streams: the minor stream is routed to a Joule-Thomson (J-T) orifice where the flow immediately flashes from liquid to vapor or two phase mixture, because the downstream of the J-T leg is maintained at vacuum level; the primary stream is injected into the tank after being cooled by the cold vapor of the J-T leg in a heat exchanger. The flow through the J-T leg is also used to cool the outer metal matrix of the injector which in turn cools the vapor in the tank ullage. The cooling of vapor in the ullage by the cold injector surface reduces the ullage pressure, allowing liquid to enter and fill the tank.

Numerical modeling of Charge-Hold-Vent method using GFSSP has been described in [18]. The model predicted accurately the amount of propellant consumed. The predicted wall temperature compared reasonably well with measured temperature.

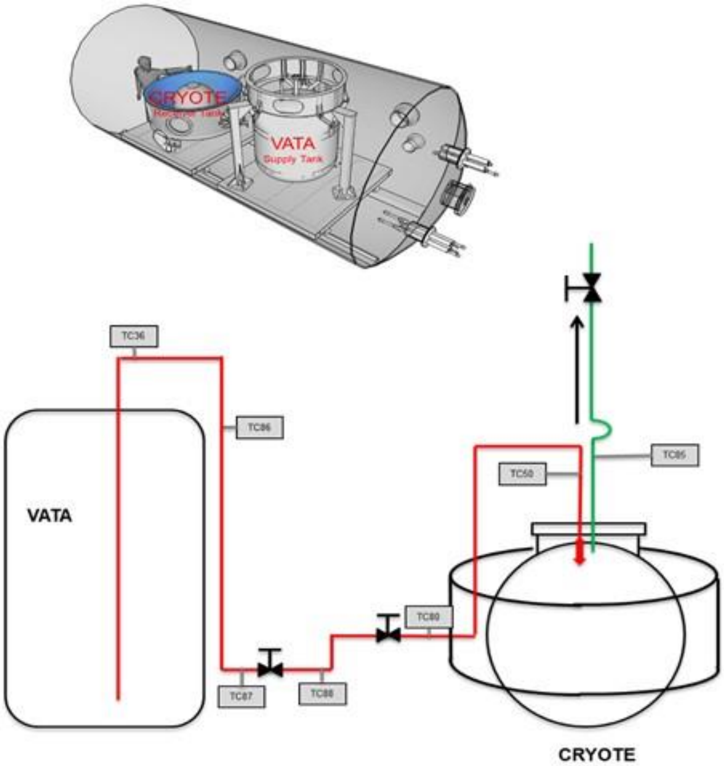


Figure 14. Schematic of Storage and Receiver Tank with Transfer Line in a Vacuum Chamber

Figure 14 shows the schematic of VCNVF test conducted at NASA/Marshall Space Flight Center. The instrumentation and test results are discussed in detail in [17]. GFSSP modeling of VCNVF Test is described in [19].

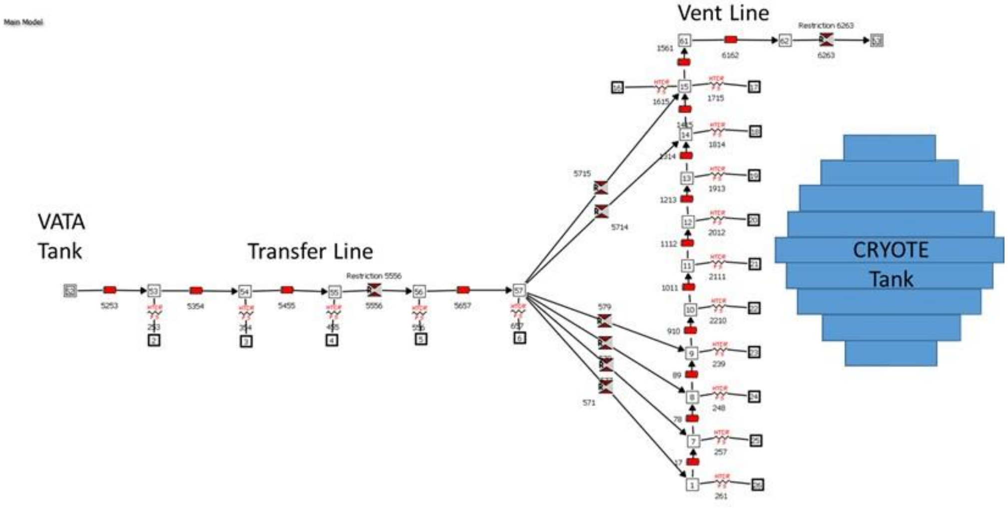


Figure 15. GFSSP Model of CRYOTE tank with inlet and outlet transfer line.

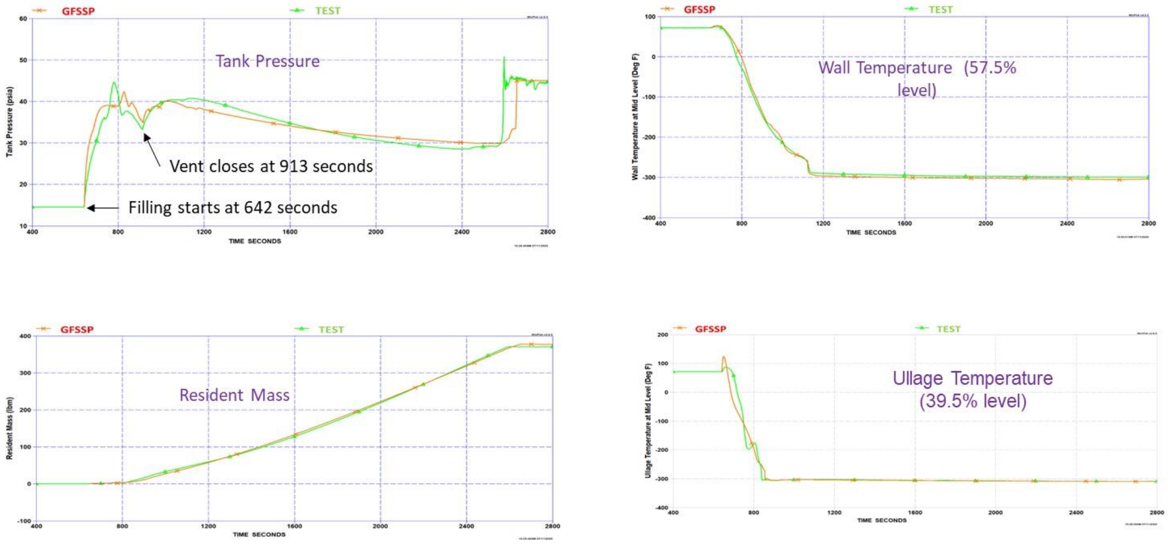


Figure 16. Comparison between measured and predicted data for VCNVF Test in CRYOTE2

GFSSP model of the Test Setup is shown in Figure 15 and comparison between measured and predicted pressure, resident mass, wall, and ullage temperature are shown in Figure 16. It may be mentioned that boiling at the wall and condensation of ullage vapor around spray droplets were incorporated through User Subroutines. The details of the boiling and condensation models are described in [20]. A good agreement between measured and predicted data is observed.

No Vent Fill test with TVS augmented injector was also conducted in CRYOTE tank in the same test setup used for VCNVF test. Figure 17 shows the GFSSP model and condensation model for the injector surface. An *ad hoc* condensation model was developed and incorporated in User Subroutine.

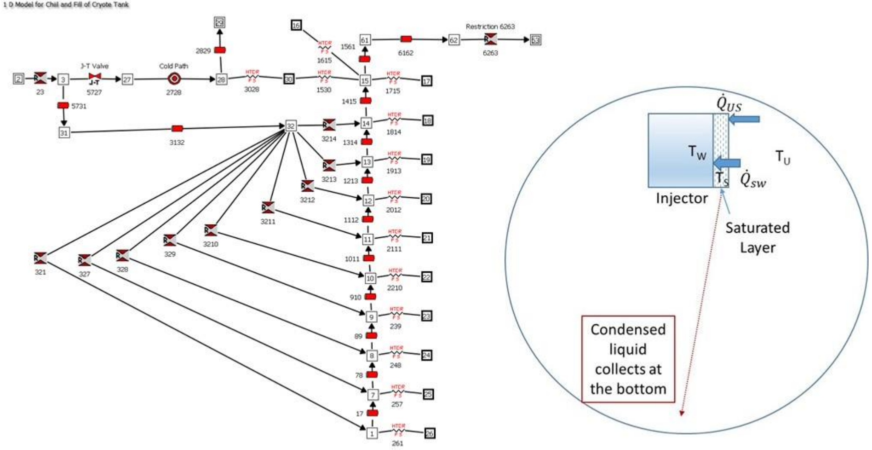


Figure 17. GFSSP Model and Condensation Model of No Vent Fill test with TVS augmented injector.

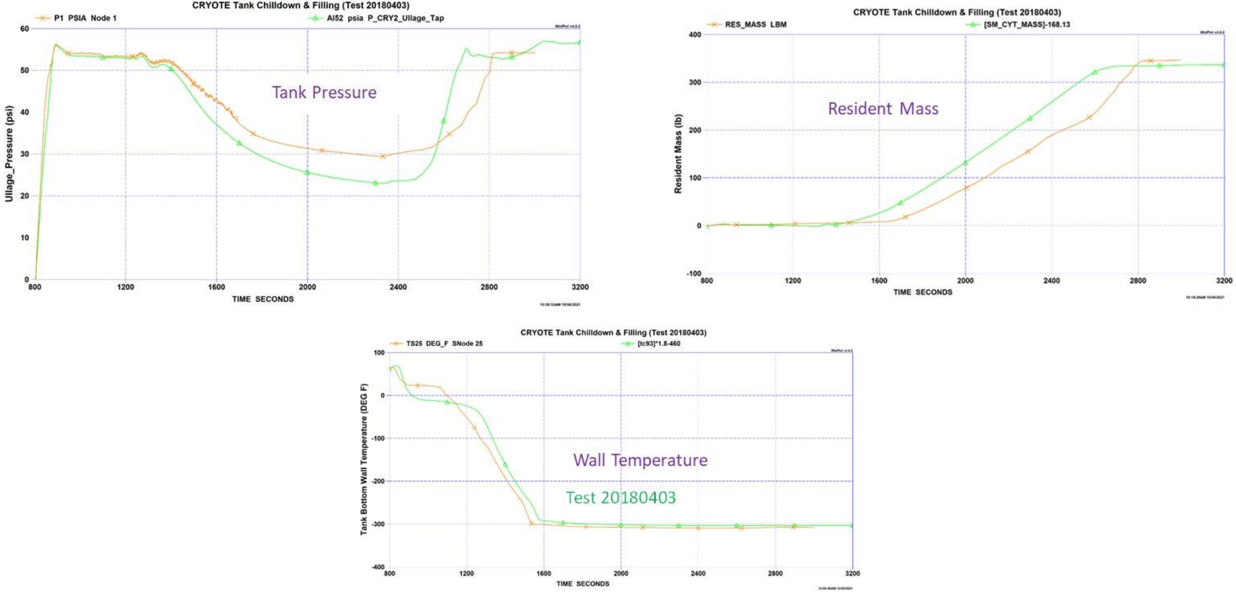


Figure 18. Comparison between measured and predicted data for No Vent Fill with TVS augmented injector.

Figure 18 shows the comparison between measured and predicted tank pressure, resident mass, and wall temperature. The observed discrepancy between test and predictions for tank pressure is within 20% and tank filling time is within 4%.

4. Summary and Conclusions

Several Liquid Propulsion System modeling applications using GFSSP have been described in this paper. The applications include a) Tank Pressurization, b) Chilldown of Cryogenic Transfer Line, and c) No Vent filling of Cryogenic Tank.

Both direct and submerged pressurization models use a single node to represent ullage and propellant. Numerical prediction of collapse factor compares well with published correlation. A large system level model was developed with pressure control valve to simulate an actual engine test. Single node model runs quickly and is suitable for a large system with multiple tanks and complex flow network. However, to accurately model ullage stratification, evaporation and condensation at the ullage-propellant interface, multi-node modeling will be necessary. Multi-node ullage modeling was used for self-pressurization in a closed tank. Multi-node modeling is more challenging for a tank with draining and needs more development work.

GFSSP models have been developed to model chilldown of both long and short cryogenic transfer line. The chilldown time and temperature distribution compares well with test data. The accuracy of prediction is largely dependent on the accuracy of boiling heat transfer coefficient correlation. Development of a general-purpose heat transfer coefficient correlation that is applicable to all cryogenic fluids will substantially reduce the uncertainty of numerical predictions.

Multi-node models of Tank Filling were developed for Charge-Hold-Vent, Vented Chill and No Vent Fill, and No Vent Fill with TVS augmented injector. Boiling model at the wall and an *ad hoc* condensation model around spray droplet, injector wall, and liquid-vapor interface were developed in User Subroutines. The numerical prediction of tank pressure and resident mass was within 20% of the measured data. The model validation was primarily done for a small tank (about 8 cubic feet) using liquid nitrogen. Further validation of the model is necessary for larger tanks using other cryogenic propellant.

5. References

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