Multi-Node Modeling of Cryogenic Tank Pressurization System using Generalized Fluid System Simulation Program

Alak Bandyopadhyay[1]
Department of Electrical Engineering and Computer Science, Alabama A & M University, Normal, AL 35762
&
Alok K. Majumdar[2], Andre C. Leclair[3] and Juan G. Valenzuela[3]
Propulsion System Department, NASA Marshall Space Center, Huntsville, AL 35812

This paper presents a multi-node model of autogenous pressurization of cryogenic propellant in a flight tank using the Generalized Fluid System Simulation Program (GFSSP), a general purpose flow network code developed at NASA/Marshall Space Flight Center. Tests were conducted to measure the pressure and temperatures at the various axial locations of the stratified ullage at 75% and 45% fill level. Liquid nitrogen was pressurized by gaseous nitrogen from a supply tank while the drain valve from the tank remained closed during the pressurization process. The ullage was discretized into 25 uniformly distributed nodes: 5 in the radial direction and 5 in the axial direction assuming the flow to be axisymmetric. Heat and mass transfer between the liquid and vapor has been modeled at the liquid vapor interface. Heat transfer between wall and vapor at the ullage has been accounted for by assuming heat transfer occurs by natural convection. The model also accounts for heat leak to the tank through the insulation and metal wall by heat conduction. The predicted pressures and temperatures are compared with the measured data.

Nomenclature

A	=	area
C_P	=	specific heat at constant pressure
g	=	gravitational acceleration
Gr	=	Grashof number == $\frac{g\beta\Delta T L^3\rho^2}{\mu^2}$
h	=	heat transfer coefficient
h_{fg}	=	heat of evaporation
k	=	thermal conductivity of propellant vapor
L	=	characteristic length for Natural Convection correlation
$\dot{m}$	=	evaporative mass transfer rate
Nu	=	Nusselt number = hL/k
p	=	fluid pressure in psia
Pr	=	Prandtl number = $\mu C_P/k$
Q	=	Heat Transfer Rate
Ra	=	Rayleigh number = Gr Pr
T	=	temperature
ΔT	=	temperature difference
β	=	coefficient of volume expansion
μ	=	absolute viscosity
ρ	=	density
Suffixes:		
I	=	liquid-vapor interface
l	=	laminar
L	=	liquid
sat	=	saturated
t	=	turbulent
u	=	ullage
v	=	vapor

[1] Associate Professor, Computer Science Department.
[2] Aerospace Technologist, Propulsion Systems Department, AIAA Senior Member.
[3] Aerospace Technologist, Propulsion Systems Department.

I. Introduction

Cryogenic Tanks are pressurized by inert gas such as Helium or Nitrogen to maintain the required pressure of the propellant delivered to the turbo-pump of a liquid rocket engine. Thermo-fluid system simulation tools are used to analyze the pressurization process of a cryogenic tank. Most system level codes (GFSSP and ROCETS) use a single node[1] to represent ullage which is the gaseous space in the tank. Ullage space in a cryogenic tank is highly stratified because the entering inert gas is at ambient temperature whereas the liquid propellant is at a cryogenic temperature. A single node model does not account for the effect of temperature gradient in the ullage. High fidelity Navier-Stokes based CFD model of Tank Pressurization is not practical for running a long duration transient model with thousands or millions of nodes. A possible recourse is to construct a multi-node model with system level code that can account for ullage stratification with conjugate heat transfer.

For the past few years, United Launch Alliance has been developing a propulsion system called Integrated Vehicle Fluids (IVF) to improve the functional and reliability limits of upper stages for long-duration space missions. IVF uses boil-off propellants to drive thrusters for the reaction control system as well as to run small internal combustion engines (ICEs). The produced thrust is used for maneuvering the vehicle and to settle propellants during coast flight. Figure 1 shows a simplified schematic of the IVF system including the propellant tank and a fluid loop consisting of a compressor and heat exchanger instead of a helium tank in a conventional propulsion system. The compressor intakes propellant vapor from the tank ullage and drives it through a heat exchanger to heat it before it sends it back to the tank for pressurization. The heat exchanger receives heat from coolant of the ICE. The ICE provides power to the compressor and battery. The network flow solver program GFSSP[2] has been used to model the heat exchanger component and the complete IVF system by using one dimensional model (changing only in the tank axial direction) for temperature and pressure by Leclair et.al.[4] and Majumdar et.al.[3]. However both these models are unable to see any two dimensional effect within the tank.

The objective of the current study is to develop a multi-node computational model to simulate the pressurization of the tank due to the propellant injection from the top of the tank and simultaneous venting of ullage gas during this process. In the current model, the IVF loop is excluded. The testing data are available with liquid Nitrogen; hence, in the current model liquid N_2 has been used as the working fluid. The model also considers the conjugate heat transfer in the tank wall.

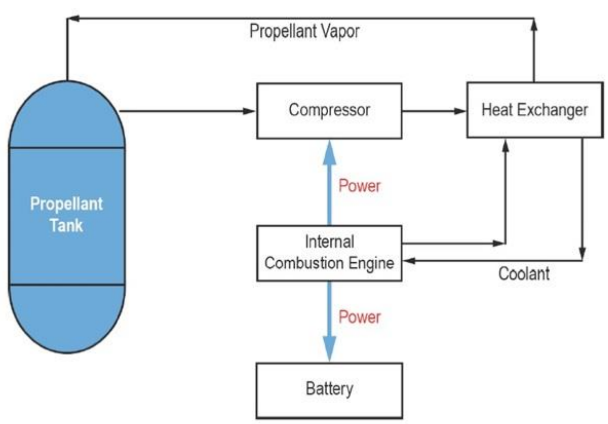


Figure 1. **Simplified Schematic of IVF System**

II. Test Setup

The test data used for model validation were taken from the Phase B portion of the Evolvable Cryogenics (eCRYO) Integrated Vehicle Fluids (IVF) task. Phase B sought to perform subscale functional performance tests of the autogenous pressurization concept. An external facility supply source of gaseous nitrogen at ambient temperature was used in place of the IVF compressor and heat exchanger. The nitrogen flow was used to pressurize a tank of liquid nitrogen that was continuously vented.

The liquid nitrogen tank was CRYOTE 3, a Cryogenic Fluid Management (CFM) test article built by United Launch Alliance (ULA) (Figure 2). CRYOTE 3 is a flight-like tank of size typical for upper stages. It is constructed with very thin stainless-steel walls to minimize its dry weight. The tank rests on a column-mounted support ring with a fiberglass insert to minimize conductive heat leak. During testing the tank walls were insulated with fiberglass insulation.

Figure 2: CRYOTE 3 Test Article

Propellant mass was measured by four load cells at the bottom of the support structure. As shown in Figure 3, temperatures were measured with silicon diodes on a vertical rake near the centerline of the tank, a horizontal rake at the 50% fill level, and on the inside and outside surfaces of the tank walls.

CRYOTE 3 is also equipped with two pressurant injectors: a four port (Quad jet) and a single tube pointed down. Both injectors can be used independently as well as in combination with each other, and both are connected to the facility pressurant supply and the simulated IVF autogenous pressurization system.

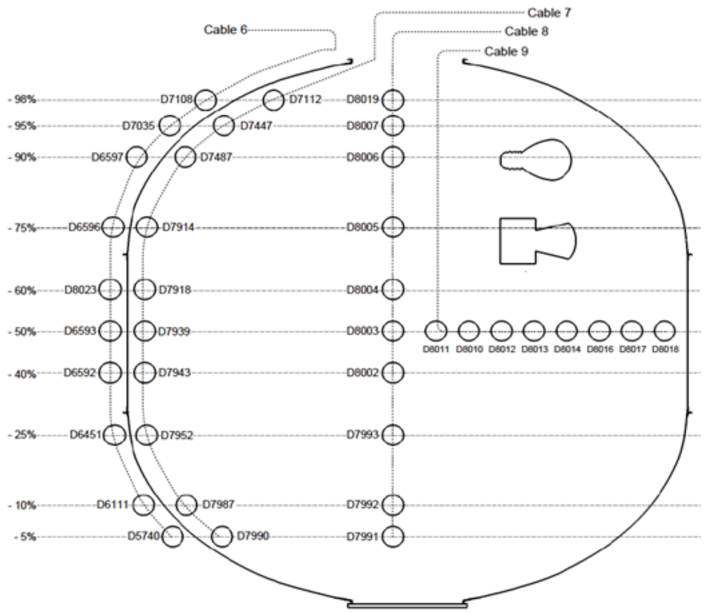


Figure 3: CRYOTE 3 Silicon diode Sensors.

III. Mathematical and Computational Model

In the present study, the flow and heat transfer within the ullage space is considered along with conjugate heat transfer between tank wall and the ullage. The interaction between ullage to liquid is modeled through the heat and mass transfer equations at the interface as described later in this section. Two different fill-levels of the tank are considered for the model: (a) tank is initially filled with 75% liquid (by volume) and (b) with 45% liquid (by volume). The ullage space is assumed to be filled with vapor. All the operating conditions including initial state of the ullage, the injector pressure and temperature conditions and vent valve operating conditions are taken from the experimental data. In this section, the computational model developed using GFSSP is described followed by the heat and mass transfer model at the liquid-ullage interface and heat transfer between tank wall to the ullage space.

Computational Model Using GFSSP:

The entire ullage space is uniformly divided into 5 segments along the axial direction and uniformly divided into 5 segments in the radial direction. Nodes are placed at the center of each cell formed by this division. Figure 4 shows below the multi-node model of GFSSP with a total of 25 fluid nodes, 20 solid nodes and 44 branches. The mass and energy conservation equations in conjunction with the equation of state for a real fluid are solved in fluid nodes. The momentum equations of the fluid are solved in the branches. The energy conservation equations are solved in the solid nodes. The system of equations are solved by a hybrid numerical method[2] which is a combination of simultaneous Newton-Raphson method and successive substitution method.

Nodes 1 through 25 are representing the fluid nodes in the ullage space and nodes 28 through 46 (as shown with solid border line) represent the tank wall with two different layers for the metal and insulation as indicated. Nodes 1 through 5 are the ullage nodes closest to the liquid surface, nodes 5, 10, 15, 20 and 25 are close to tank walls, nodes 1, 6, 11, 16 and 21 are along the center line of the tank. The model is assumed to be axisymmetric. Node 26 represents the liquid node that contains the entire liquid mass of the tank. Node 27 is a boundary node representing the tank drain outlet. The injector flow comes in to the tank from the top of the tank and node 30 represents the inlet boundary to the tank, and similarly node 51 represent the exit boundary from the tank through which the fluid is vented out. The vent valve is modeled using a restriction option in GFSSP and the valve open-close area history with time is according to the test setup. Figure 5 shows the vent valve opening profile as a function of time for the (a) 75%-fill test study and (b) 45%-fill test study.

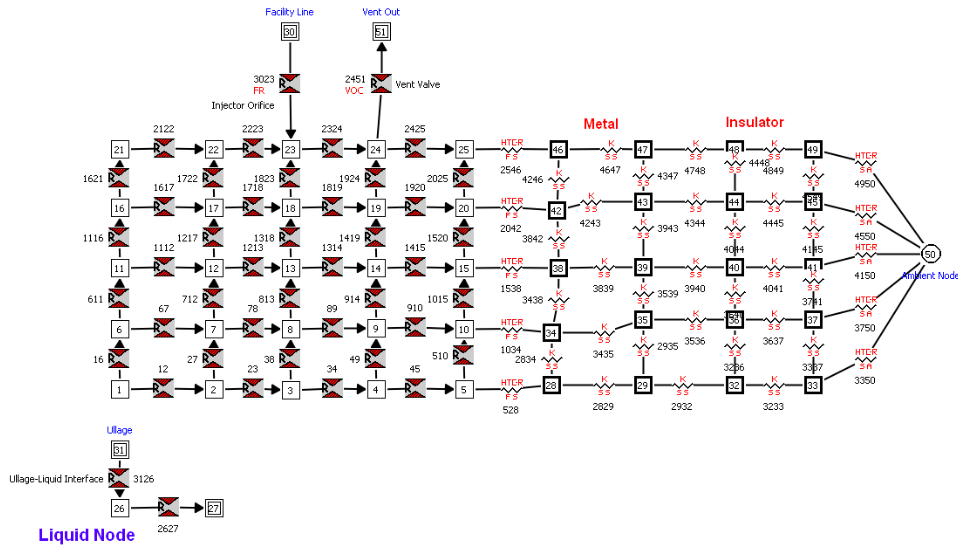


Figure 4. Multi-node Model of the Propellant Tank.

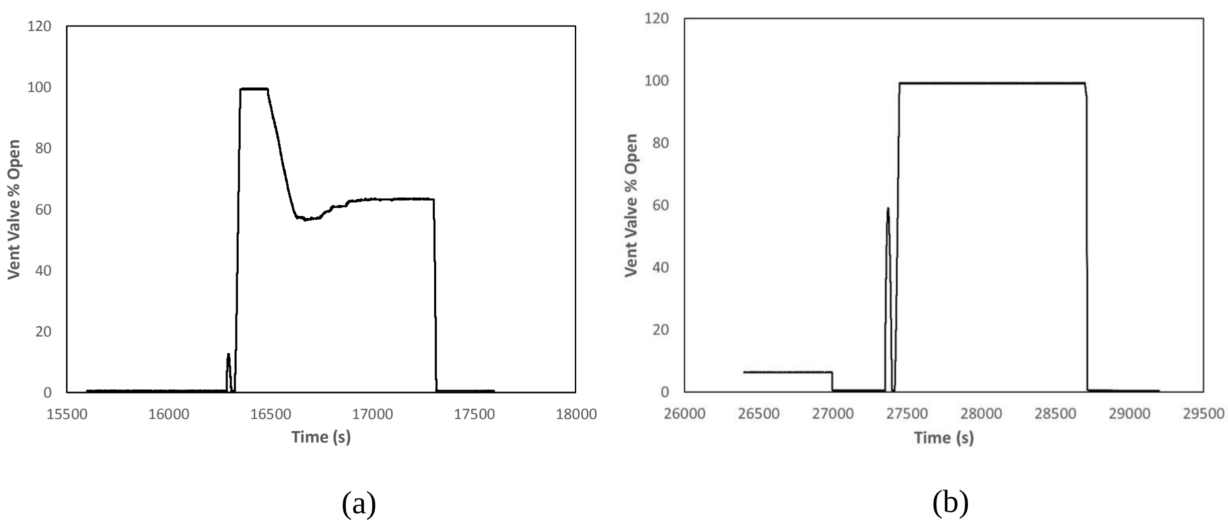
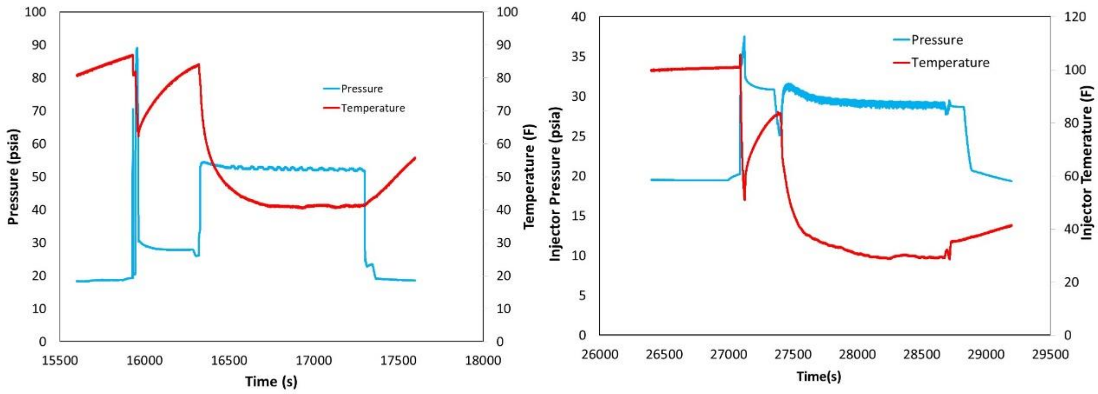


Figure 5. Vent Valve percentage Open with time.

Node 30 in the GFSSP model (figure 4) represents the injector inlet to the tank through a valve with pressure and temperature conditions taken from the test data. The pressure and temperature inlet conditions for the injector flow are shown in figures 6(a) and 6(b) for 75% fill case and 45% fill case respectively.



(a) (b)

Figure 6: Propellant Injector Pressure and Temperature Test Data for (a) 75% and (b) 45% fill cases

Heat Transfer between Tank-wall to ullage

It is expected that there is heat transfer between the tank-wall and the ullage space as the tank is exposed to ambient condition. This is modeled in the current study by considering (a) heat transfer due to natural convection at the wall to ullage interface and (b) heat conduction in the tank wall with convective boundary condition at the external wall. The heat transfer coefficient between the wall and ullage was computed from a natural convection correlation for a vertical plate[5]. The following set of equations was used for this correlation:

$$\mathrm{Nu} = [(\mathrm{Nu}_l)^m + (\mathrm{Nu}_t)^m]^{1/m} \quad m = 6 \tag{1}$$

$$\mathrm{Nu}_t = C_t^V \mathrm{Ra}^{1/3}/(1 + 1.4 \times 10^9 \mathrm{Pr}/\mathrm{Ra}) \tag{2}$$

$$\mathrm{Nu}_l = 2/\ln(1 + 2/\mathrm{Nu}^T) \tag{3}$$

$$\mathrm{Nu}^T = \bar{C}_l \mathrm{Ra}^{1/4}, \tag{4}$$

$$C_t^V = \frac{0.13\,\mathrm{Pr}^{0.22}}{\left(1 + 0.61\,\mathrm{Pr}^{0.81}\right)^{0.42}}, \tag{5}$$

and

$$\bar{C}_l = \frac{0.671}{\left[1 + \left(0.492/\mathrm{Pr}\right)^{9/16}\right]^{4/9}}, \tag{6}$$

Where Gr = Grashof number = $L^2\rho^2 g\beta\Delta T/\mu^2$
Pr = Prandtl number = $\mu C_P/k$
Ra = GrPr
Nu = hL/k. Subscripts t and l refer to turbulent and laminar, respectively.

Liquid-Ullage Heat and Mass Transfer Model for Self-Pressurization[6]

Figure 7 shows the schematic of ullage and liquid propellant where there is heat transfer between the ullage and the liquid propellant that also results in evaporative mass transfer.

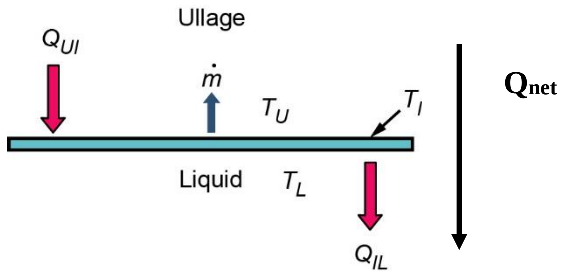


Figure 7. Evaporative Heat and Mass Transfer at liquid-vapor interface.

In this evaporative mass transfer model, a saturated layer is assumed at the interface between liquid and vapor so that $T_I = T_{sat}(P_v)$, where P_v is propellant vapor pressure in the ullage. The saturated layer receives heat from the ullage (Q_{UI}) and also rejects heat to the liquid (Q_{IL}). The difference in this heat rate contributes to the mass transfer in accordance with the law of energy conservation. The equations governing this process are as follows:

a) Heat transfer from ullage to interface layer:

$$Q_{UI} = h_{UI}A(T_U - T_I) \tag{7}$$

b) Heat transfer from interface to liquid:

$$Q_{IL} = h_{IL}A(T_I - T_L)\ . \tag{8}$$

The evaporative mass transfer is expressed as

$$\dot{m} = \frac{Q_{UI} - Q_{IL}}{h_{fg}}\ . \tag{9}$$

h_{fg} is the enthalpy of evaporation, and the heat transfer coefficients h_{UI} and h_{IL} are computed from natural convection correlations given by:

$$h_{UI} = K_H C \frac{k_f}{L_s} \mathrm{Ra}^n = h_{IL}\ , \tag{10}$$

Where C = 0.27, and n = 0.25, K_H is a correction factor and was set to 0.5 to match the measured boil-off rate.

The heat transfer coefficient is assumed to be the same on both sides of the liquid vapor interface.

The net heat transfer from ullage to the liquid is given as below, and this has been used as a heat sink in the energy equation for the fluid in the ullage adjacent to the liquid node.

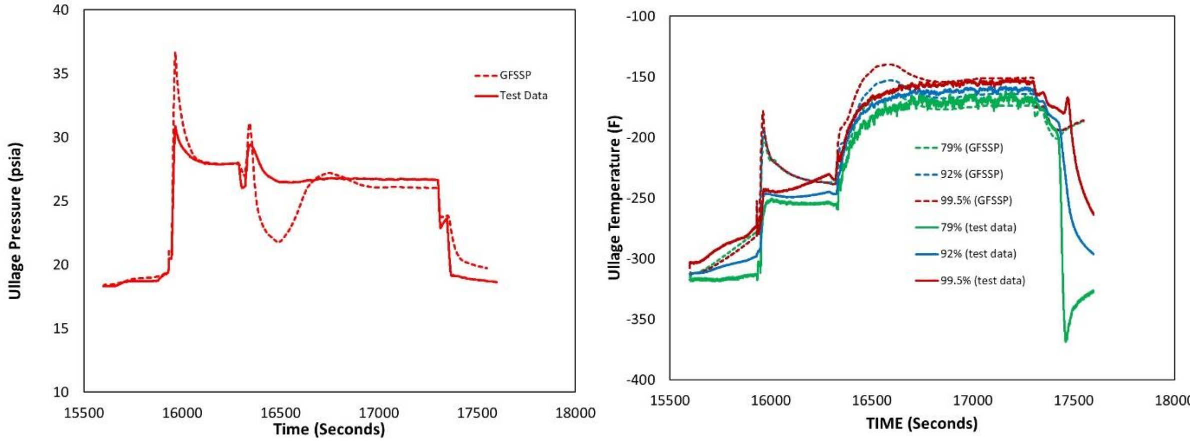
$$Q_{net} = \dot{m}[C_{P,l}(T_I - T_L) + h_{fg}] \tag{11}$$

IV. Results and Discussion

Two different fill levels are considered for the simulation: (a) 75% Fill-level – 75% of the tank volume is initially filled with liquid propellant (in the current study liquid Nitrogen is used) and (b) 45% Fill-level – 45% of the total volume is filled with liquid propellant. The inputs for the simulations such as the vent flow valve open-close time variations and the injector pressure and temperature variations with time, are identical to test conditions and have been shown in figures 5 and 6 respectively in the previous section. The simulation is run for about 2000 seconds for the 75% fill-level case and about 2800 seconds for the 45% case. The test times show that the 75% case is tested first and then the 45% fill-level. Hence the modeling results are presented in similar way. The governing equations of mass, momentum and energy are solved by marching in time with a step size of 0.01 second. The results are converged with an accuracy of 1 x 10^{-4}.

Case 1. 75% Fill-Level: 75% of the tank is initially filled with liquid propellant.

The computational results of ullage pressure and temperature from GFSSP simulations are compared with the test data and are as shown in figures 8(a) and 8(b) below.



(a) (b)

Figure 8. Comparison of computed data with test data for (a) ullage pressure and (b) ullage temperature.

The axial locations (measured from bottom of tank) are selected as per the node locations in the GFSSP model and the percentage indicates the volume of the tank as compared to total volume. Hence 79% means an axial position (from bottom of tank) that covers 79% of the total tank volume. The solid lines indicate the test data and the dotted lines indicate the numerical results from GFSSP. Good agreement is shown in ullage pressure prediction while comparing with the test data except the time zone when the vent valve opens 100% at a very fast rate as shown in vent-valve open history (figure 5a). The ullage temperature plot (figure 8b) shows the comparison of ullage temperature at three different locations in the ullage space: close to the liquid interface (79%), at the midpoint (92%) and at the top of the tank (99.5%). The GFSSP modeling shows higher ullage temperature corresponding to the test data in the time zone where the injector pressure and temperature were varying abruptly (see figure 6). When the injector pressure is relatively steady, agreement between the predictions and measurements is better. It shows about 20 degrees F stratification in the ullage space, which agrees with the test data. The wall temperature at various locations are also compared with the test data in figure 9. The test data were available only at the top of the tank and therefore the results are shown at 97% and 99.5% (top two nodal points in the model). The dotted lines correspond to modeling results and solid lines correspond to test data.

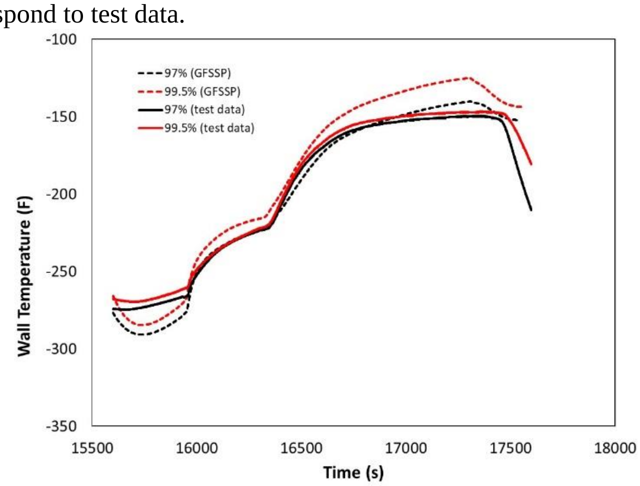


Figure 9. Internal wall temperature as a function of time (modeling vs test data)

The total heat transfer from the tank wall to the ullage space is computed and plotted as a function of time as shown in figure 10. In the steady state region, the computed heat transfer rate is about 2000 Watts. Negative Q implies that wall is heated by the ullage gas which happens during rapid pressurization.

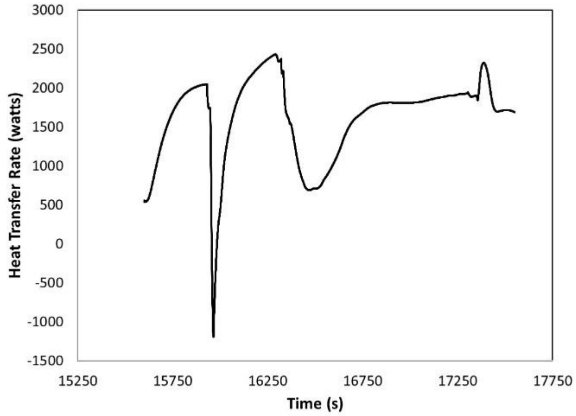


Figure 10. Heat Transfer rate from tank wall to ullage.

The heat transfer coefficient at the inner surface of the tank wall and ullage at three different axial locations (along the tank height) are shown in the figure 11.

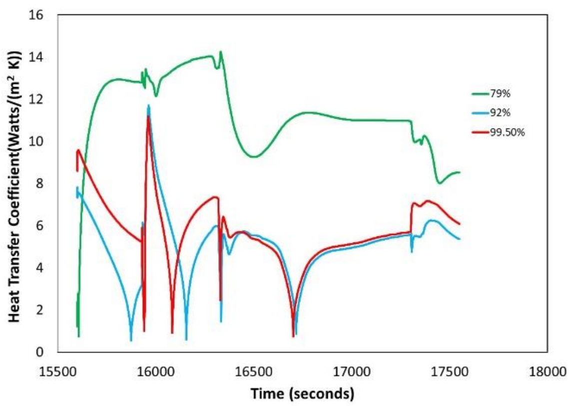


Figure 11. Computed heat transfer coefficient between the ullage and tank wall

Figure 12 shows the streamline trace and the temperature contours (at time = 17000 seconds, steady state region). The domain shown is the representation of the ullage space (tank top domain). The radial direction is along the X axis and tank height is along the Y axis. As expected the warmer region is at the top of the tank. The velocity vector near the top domain is due to the complex interaction of injector flow coming in and the vent flow going out. Increasing more number of grids near the top could have shown a better representation of the velocity vector plot, as well as temperature contours.

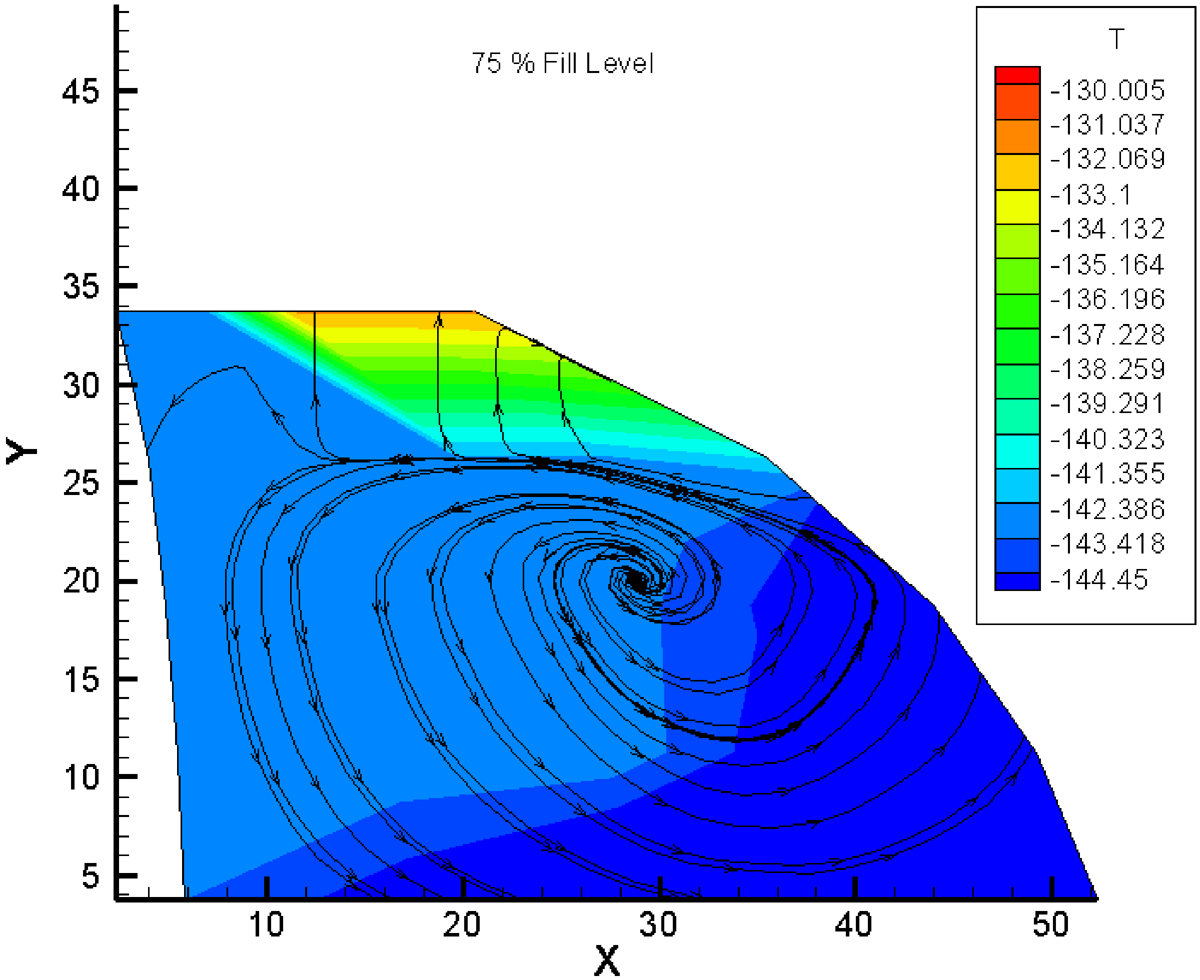


Figure 12. Temperature contour and Stream Traces at time = 17000 s.

Case 2. 45% Fill-Level: 45% of the tank is filled initially with liquid propellant

In the second test case, with 45% initially filled tank, the computed results from GFSSP are compared with test data for ullage pressure and ullage temperature as shown below.

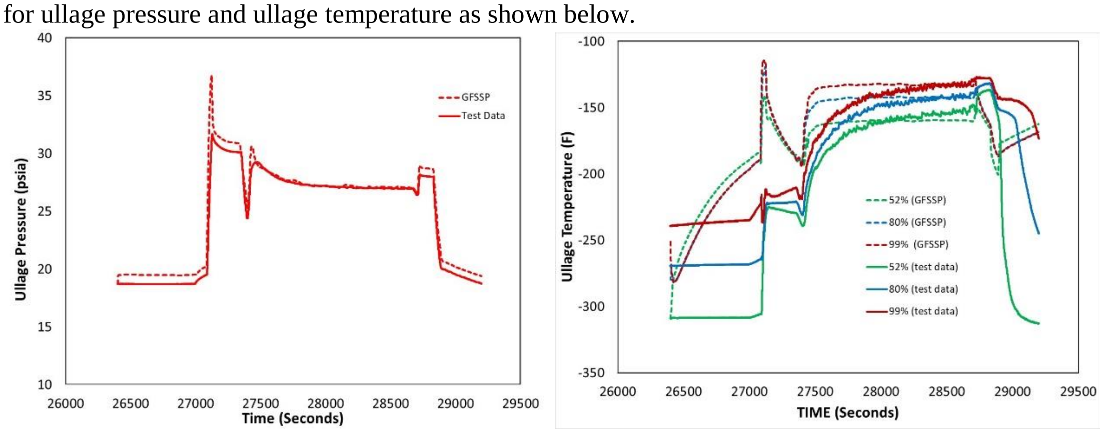


Figure 13. Comparison of computed data with test data for (a) ullage pressure and (b) ullage temperature.

Good agreement of the ullage pressure between model data and test data has been observed in figure 13. The ullage temperature also shows similar behavior in the steady state region.

The boil off of the propellant is computed as the amount of mass evaporated from the liquid surface and this has been plotted as a function of time in the figure 14 given below. For the test data, this value is computed as the difference between flow vented out from the ullage space and the injector flow coming in during steady state operation.

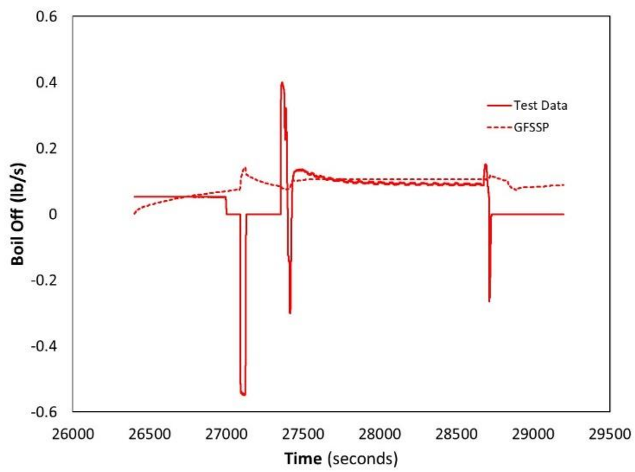


Figure 14: Computed and test data for boil-off.

The computed results compare well with the test data in the steady-state region when the vent valve is fully open. However, during the sudden opening and closing of the valve there are discrepancies.

The temperature contour and streamline traces for the 45%-fill case have been shown in figure 15.

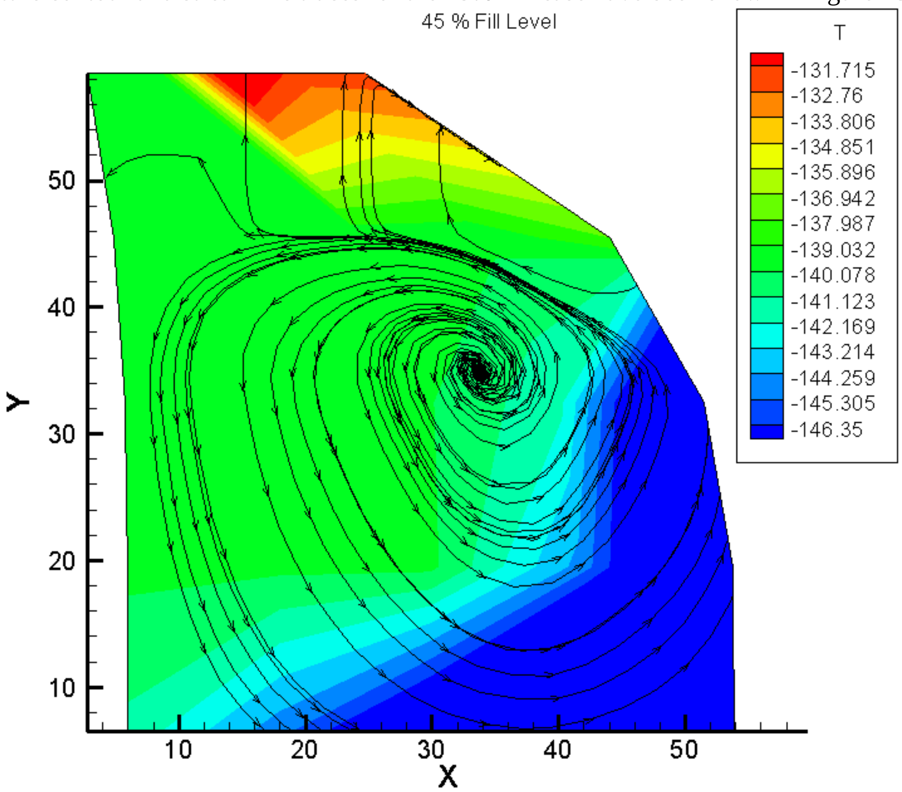


Figure 15. Temperature contour and Stream Traces at time = 28000 s.

V. Conclusions

This paper demonstrates the feasibility of system level modeling of tank pressurization using multiple nodes. The ullage of a flight tank has been modeled using 25 nodes and 40 branches where mass and energy conservation equations were solved at the nodes and momentum equations are solved at the branches. Gravity, heat and mass transfer at the liquid vapor interface, and heat transfer between solid and fluid are accounted for in the governing equations. The model results have been verified by comparing with test data. The advantage of using multiple nodes in a system level code is that it allows prediction of recirculation and stratification with a fraction of the computational cost of a high fidelity Navier-Stokes code.

Acknowledgments

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