NUMERICAL MODELING OF PROPELLANT BOIL-OFF IN A CRYOGENIC STORAGE TANK

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ABSTRACT

A numerical model to predict boil-off of stored propellant in large spherical cryogenic tanks has been developed. Accurate prediction of tank boil-off rates for different thermal insulation systems was the goal of this collaboration effort. The Generalized Fluid System Simulation Program, integrating flow analysis and conjugate heat transfer for solving complex fluid system problems, was used to create the model. Calculation of tank boil-off rate requires simultaneous simulation of heat transfer processes among liquid propellant, vapor ullage space, and tank structure. The reference tank for the boil-off model was the 850,000 gallon liquid hydrogen tank at Launch Complex 39B (LC-39B) at Kennedy Space Center, which is under study for future infrastructure improvements to support the Constellation program. The methodology employed in the numerical model was validated using a sub-scale model and tank. Experimental test data from a 1/15th scale version of the LC-39B tank using both liquid hydrogen and liquid nitrogen were used to anchor the analytical predictions of the sub-scale model. Favorable correlations between sub-scale model and experimental test data have provided confidence in full-scale tank boil-off predictions. These methods are now being used in the preliminary design for other cases including future launch vehicles.

KEYWORDS: Cryogenic tanks, thermal insulation, propellant boil-off, finite volume method, conjugate heat transfer

PACS:

INTRODUCTION

The cost of loss of propellants due to boil-off in large cryogenic storage tanks is in the order of one million dollar per year. One way to reduce this cost is to design a new tank or refurbish existing tanks by using bulk-fill insulation material with improved thermal performance. Such an effort was undertaken by Cryogenic Test Laboratory of Kennedy Space Center (KSC) to reduce the propellant boil-off in cryogenic storage tanks at Launch Complex 39 at KSC. The cryogenic storage tanks (Figure 1) in KSC were built in 1960's. The vacuumed annulus space between the inner and outer spheres of each storage tank is filled with Perlite insulation. Perlite is susceptible to compaction after repeated thermal cycles. It is widely believed that the compaction has led to decreased thermal performance.

Fesmire and Augustynowicz [1] have measured apparent thermal conductivity of several bulk-fill insulation materials and have found that the thermal conductivity of Glass Bubbles is 67% less than Perlite in vacuum. In another study Fesmire et al [2] studied the vibration and thermal cycling effects on several bulk-fill insulation materials and found that Glass Bubbles are not susceptible to compaction due to thermal cycling. As a part of the Independent Research and Development (IRAD) Project entitled, "New Materials and Technology for Cost Efficient Storage and Transfer (CESAT)", KSC [3] has built two 1000 liter Demonstration Tanks (Figure 1) and tested to evaluate the performance of Perlite and Glass Bubble insulation for liquid nitrogen and hydrogen.

The purpose of the present paper is to develop a numerical model of the boil-off for cryogenic storage tank in KSC. The model developments were carried in two phases. First, the model was verified with the test data for Demonstration Tanks for Liquid Nitrogen and Hydrogen. The verified model was then extended to model the actual storage tank and the predictions were compared with field data. A general purpose flow network computer code, Generalized Fluid System Simulation Program (GFSSP) [4,5] was used to develop the numerical models.

NUMERICAL APPROACH

Boil-off calculation requires the calculation of heat leak through metal walls and insulation. A simple one-dimensional calculation of heat conduction through a composite layer consisting of metal and insulation is not adequate for estimating the boil-off because the heat leak process is not entirely one dimensional. The tanks are partially filled with vapor at a temperature higher than the liquid propellant. This vapor space, called the ullage, is also stratified due to gravitational effects. In addition to heat conduction through metal and insulation, the thermodynamics and fluid mechanics of the propellant also play a role in determining boil-off rate. Therefore, it is essential to use a code that has the capability to model all of the processes that influence boil-off.

The Generalized Fluid System Simulation Program (GFSSP), developed at MSFC has been used to develop the thermal models for estimating boil-off in the Demonstration tanks and the Liquid Hydrogen Storage tank at LC-39. GFSSP is a finite volume based computer code for analyzing fluid flow and heat transfer in a complex network of fluid and solid systems. GFSSP was first developed for analyzing flow network using "node" and "branch". After constructing the flow network with "node" and "branch", the program solves for mass and energy conservation in "node" and momentum conservation equation in "branch". The code has been subsequently upgraded [6] to model simultaneously fluid and solid network with conjugate heat transfer that allows calculation of solid temperatures with convection and radiation heat transfer with fluid nodes and conduction and radiation heat transfer with other solid nodes.

DESCRIPTION OF CRYOGENIC PROPELLANT TANKS

Two identical 1/15th scale demonstration test tanks were manufactured for the CESAT test program [7]. Both tanks (Figure 1) were constructed with stainless steel inner and outer spheres. The annular space between the two spheres in each tank can be filled with an insulating material and the pressure can be reduced to vacuum conditions. Both tanks include fill/drain lines, vent lines, support structures and anti-rotation systems that could contribute to heat leak. Both tanks are heavily instrumented with identical measurements in identical locations. Boil-off during CESAT testing was measured using either two flow meters installed on the vent line of each tank or by evaluating the total change in weight of the tank during testing. Temperature was measured at several locations on both the inner and outer sphere.

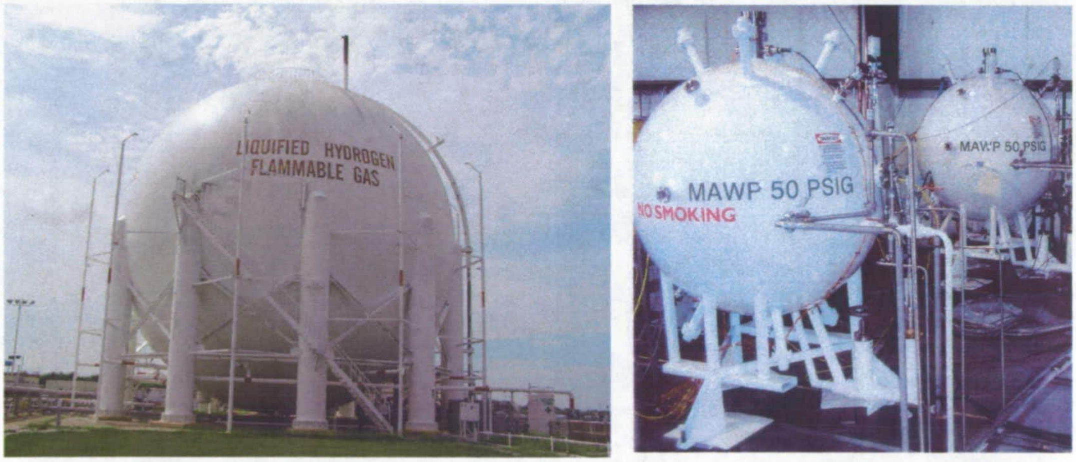

Figure 1: Liquid Hydrogen Tank in LC-39A and Demonstration Tanks at Kennedy Space Center

There are two full scale liquid hydrogen tanks located at KSC LC-39. Both tanks were built in 1965 for the Apollo program and fabricated by Chicago Bridge and Iron of Salt Lake City, Utah. Both tanks (Figure 1) were constructed with austenitic stainless steel inner spheres and carbon steel outer spheres. The annular space between the two spheres in each tank can be filled with an insulating material and the pressure can be reduced to vacuum conditions. Both tanks include fill lines, vent lines, and support structures that could contribute to heat leak. Figure 5 shows the dimensions of the two full scale tanks.

NUMERICAL MODEL DEVELOPMENT

Figure 2 shows a schematic that illustrates the technique that was developed for modeling the CESAT demonstration tanks. The figure shows that the heat path from ambient to propellant was broken into an ullage path and a propellant path. The heat transferred through the ullage path into the ullage space (Q,a-u) is used to calculate the ullage temperature, which is then used to calculate the heat transfer between the ullage and propellant (Q,u-p). The heat transferred through the propellant path (Q,a-p) is calculated independently. The heat transferred through the structure (Q,s-p) is assumed as a constant value from a separate calculation. Q,u-p, Q,a-p and Q,s-p are summed to determine the total heat transferred to the propellant. The total heat transfer is then used to calculate the propellant boil-off rate. Figure 3 shows the GFSSP model that was developed based on this modeling technique. The model consists of five fluid nodes connected by three fluid branches, as well as one ambient and twelve solid nodes joined to the fluid and each other by twenty conductors.

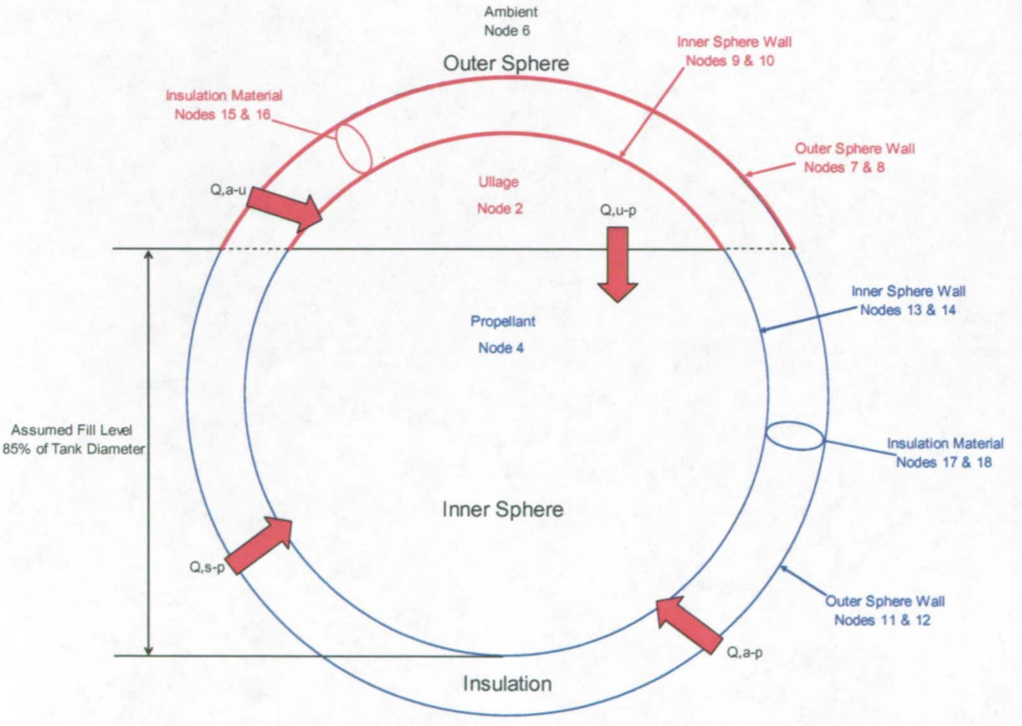

Figure 2 Schematic Illustrating Boil-Off Fill Level Modeling Technique

While the model shown in Figure 3 was appropriate for modeling the CESAT demonstration tanks, it was found to be inadequate for modeling the LC-39 cryogenic storage tanks. Because of the difference in scale between the demonstration and full scale tank ullage spaces, using a single node to represent the ullage space led to unrealistic ullage temperature predictions. Therefore, the ullage space was subdivided into eight nodes to simulate the stratified environment. The details of the numerical models presented in this paper are described in reference 8.

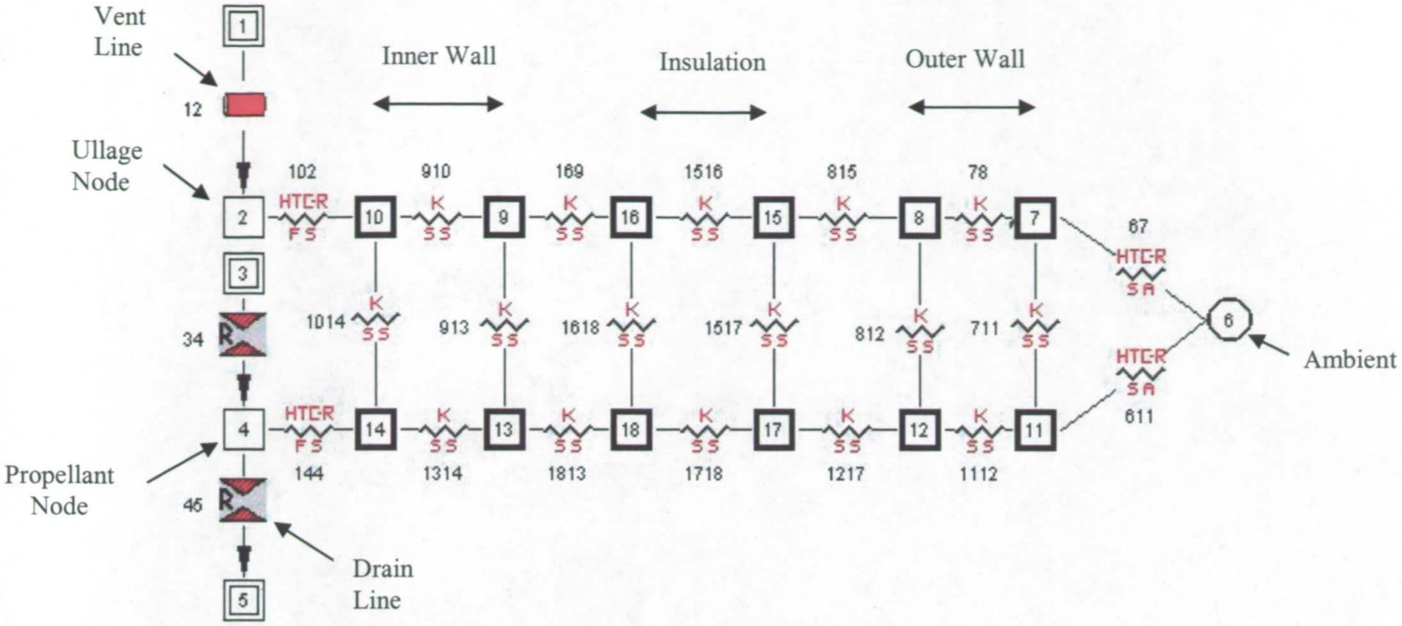

Figure 3 GFSSP Model of CESAT Demonstration Tank

NUMERICAL MODEL RESULTS

All GFSSP predictions were performed at a fill level of 85% of the tank height (approximately 94% of the total tank volume) which was a reasonable assumption for a "full" storage tank. All predictions were first made as pre-test predictions. When testing was complete each test data set was examined to determine which boil-off test had initial conditions (ambient conditions and fill level) closest to the GFSSP predictions. These test results were then compared with GFSSP's predictions. These comparisons are shown in Table 1 for different liquid and insulation configurations.

GFSSP predicts a lower ullage space skin temperature than the test data for all four cases. Due to the fact that the test data is a point temperature measurement, while GFSSP is calculating the average skin temperature for the entire ullage-exposed inner sphere, the differences are believed to be due to the fidelity of the model. Due to stratification there is a temperature variation in the ullage where as temperature of liquid propellant does not vary with depth and much closer agreement is obtained for liquid skin temperature.

The predicted boil-off rates for the two liquid nitrogen comparisons are consistently lower than the measured test data. One factor in these discrepancies was uncertainty in the ullage-wall and ullage-propellant heat transfer coefficients, which were not adjusted to match the test data. Another possible factor is that the anti-rotation devices for both test tanks may have been in contact during liquid nitrogen testing. The predicted boil-off rates for the two liquid hydrogen comparisons match very well with measured test data. Initially, the liquid hydrogen comparisons were predicting much higher boil-off rates than those seen in testing. It was found that the ullage-propellant heat transfer was disproportionately high for these GFSSP predictions. Because temperature stratification in the ullage of a liquid hydrogen tank is more pronounced than that of a liquid nitrogen tank, the effect of natural convection is negligible in a liquid hydrogen tank. Therefore, it was assumed that ullage to propellant heat transfer, Q,u-p (Figure 2) was governed by solely conduction heat transfer for the liquid hydrogen predictions.

Table 1. Comparison of GFSSP Predictions with Test Data

Propellant	Insulation	Boil-off Rate (sccm) Test			$T_{skin,ullage}$ (K)		$T_{skin,propellant}$ (K)	
		Flow meter	Load cell	GFSSP	Test	GFSSP	Test	GFSSP
Nitrogen	Perlite	3860 3938	4018 4206	3468	92 89	81	77 77	76
Nitrogen	Glass Bubble	3230	3260	2493	92	80	77	76
Hydrogen	Perlite	20414	19182	20980	34	21	20	20
Hydrogen	Glass Bubble	13396	13242	12920	31	21	20	20

Based on the results of the CESAT work, a GFSSP model was developed for the LC-39 complex liquid hydrogen storage tanks. The Full Scale Perlite GFSSP model predicts a boil-off of 258 gallons/day. This compares to the field measurement (approximately 300 gal/day) [3]. The main reason for the discrepancy is uncertainty in the ullage to propellant heat transfer coefficient due to the size differences between CESAT and the full scale storage tanks. Using this model, GFSSP predicts that a full scale liquid hydrogen storage tank with Glass Bubbles insulation would have a boil-off rate of 182 gallons/day. Figure 9 shows GFSSP's stratified ullage temperature prediction for the full scale Glass Bubbles model. Heights from the propellant surface to the "top" of each node location are noted in the figure. GFSSP predicts a 90 K differential between the ullage temperature at the propellant surface and the ullage temperature at the top of the tank.

CONCLUSIONS

A novel numerical modeling technique has been developed using GFSSP to predict boil-off rate from a spherical cryogenic storage tank. The model recognizes the separation of liquid and the vapor space and appropriately solves for mass, momentum and energy conservation equations of liquid and vapor volume in the tank in conjunction with heat conduction equations through metallic walls and insulation material. A numerical model has been built for the Demonstration Tanks developed at KSC. The numerical predictions have compared favorably with test data for liquid nitrogen and liquid hydrogen with Perlite and Glass Bubble insulation. With the experience gained from the

Demonstration Tank models, a separate numerical model was developed for the Liquid Hydrogen Storage Tank at LC-39 at KSC. This model has used multiple nodes in the ullage space to account for the effect of stratification. The numerical model of the full scale tank was then run using Perlite and Glass Bubble insulation. The boil-off rate using Perlite Insulation is in agreement with field data. When using Glass Bubble instead of Perlite as insulation, the numerical model predicts a) 28% reduction in boil-off rate in Liquid Nitrogen Demonstration Tank, b) 38% reduction in boil-off rate in Liquid Hydrogen Demonstration Tank, c) 30% reduction in boil-off of Liquid Hydrogen Storage Tank in LC-39 at KSC.

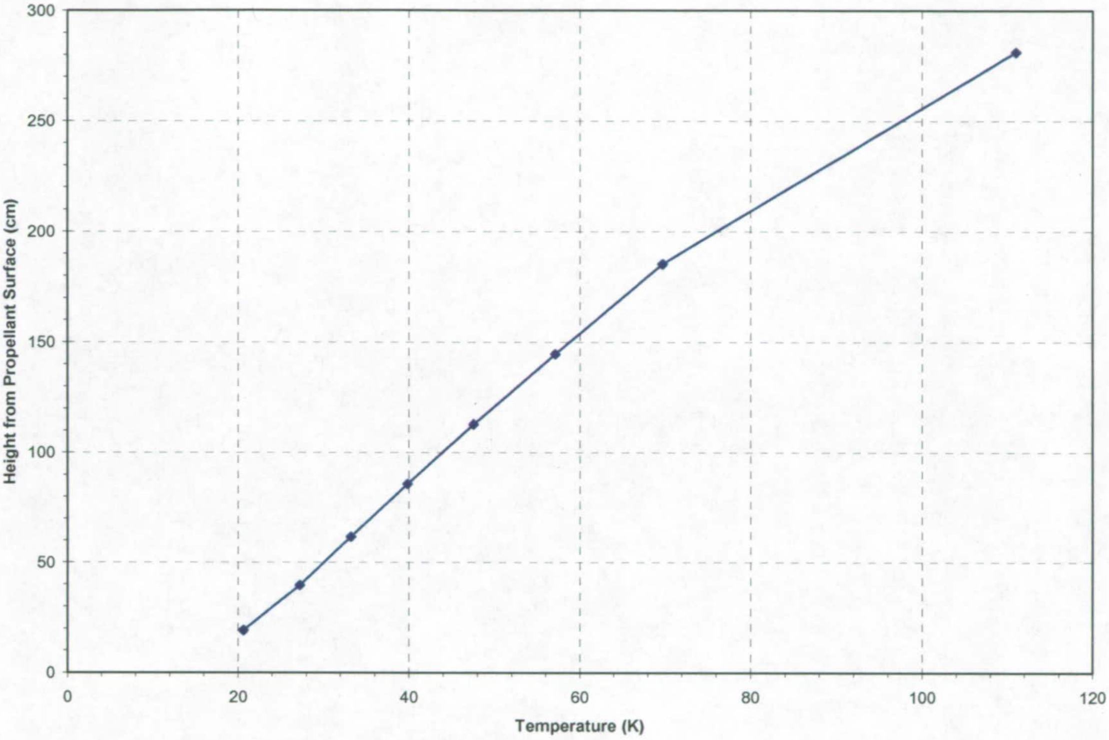

Figure 4 Stratified Ullage Temperature Prediction for LC-39 with Glass Bubbles Insulation.

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