LIQUID NITROGEN (OXYGEN SIMULANT) THERMODYNAMIC VENT SYSTEM TEST DATA ANALYSIS

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ABSTRACT

In designing systems for the long-term storage of cryogens in low-gravity (space) environments, one must consider the effects of thermal stratification on tank pressure that will occur due to environmental heat leaks. During low-gravity operations, a Thermodynamic Vent System (TVS) concept is expected to maintain tank pressure without propellant resettling. A series of TVS tests was conducted at NASA Marshall Space Flight Center (MSFC) using liquid nitrogen (LN_2) as a liquid oxygen (LO_2) simulant. The tests were performed at tank fill levels of 90%, 50%, and 25%, and with a specified tank pressure control band. A transient one-dimensional TVS performance program is used to analyze and correlate the test data for all three fill levels. Predictions and comparisons of ullage pressure and temperature and bulk liquid saturation pressure and temperature with test data are presented.

KEYWORDS: cryogenic, liquid nitrogen, heat transfer, data analysis
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INTRODUCTION

Development of advanced cryogenic upper stages is crucial for efficient high-energy propulsion systems for the delivery of payloads to Earth orbit and beyond. To minimize cryogenic propellant boiloff and to maintain propellant tank pressure control pose significant challenges associated with the storage of cryogens in the near zero-gravity environment of space. Traditionally, auxiliary thrusters are used to settle the propellants in order to accomplish tank venting. However, such systems incur weight penalties— associated with the propellant and hardware required—that increase with the number of

settling sequences required during the mission. In addition, tank venting/resettling may become necessary at inopportune times in a mission timeline and thereby increase mission complexity. The TVS concept enables tank pressure control through venting without resettling. The performance of the spray-bar TVS concept for liquid hydrogen (LH$_2$) applications was investigated and validated at MSFC in 1996 and 1998 by conducting a series of successful tests [1,2]. To evaluate the concept for LO$_2$ applications, several tests were performed using LN$_2$, an LO$_2$ simulant. The TVS concept and its extension to LN$_2$ applications are presented in the following section.

Thermodynamic Vent System Concept

Originally, the spray-bar TVS concept was introduced for LH$_2$ applications [1,3]. The TVS, as shown in FIGURE 1, consists of a recirculation pump, a Joule-Thomson (J-T) expansion/shutoff valve, and a parallel flow concentric tube heat exchanger/spray-bar apparatus. The pump extracts propellant from the tank and flows it through the heat exchanger/spray-bar apparatus. The fluid reenters the tank through orifices in the spray-bar that expel the fluid radially into the tank, resulting in propellant destratification and ullage condensation through mixing. When pressure control within the tank cannot be maintained through mixing alone (bulk liquid is saturated at the ullage pressure), a small amount of fluid is extracted from the recirculation flow and passed through the J-T valve where it is expanded to a lower pressure and temperature. This subcooled two-phase fluid mixture is then passed through the heat exchanger, which extracts heat from the recirculation flow, and subsequently is vented to the environment. Details of the spray-bar TVS hardware development effort are provided by Lak and Wood [3].

To evaluate the concept for LO$_2$ while avoiding the LO$_2$ TVS testing safety issues, LN$_2$ was chosen as the operating fluid. (LN$_2$ and LO$_2$ have comparable thermal and fluid properties.) To adapt the system for LN$_2$ testing, several modifications were made to the original TVS components and configuration. First, the recirculation pump and J-T valve were replaced to accommodate the much higher mass flow rate required in LN$_2$ testing. Second, due to a much larger mass of stored LN$_2$ and low environmental heat leaks, the thermodynamic state changes of the systems would be very slow and time consuming. To expedite testing, two graphite heaters were installed in the bottom of the tank, thereby delivering a specified quantity of energy into the bulk liquid and accelerating the thermodynamic state changes. Since the bulk liquid saturation pressure rise rate would be
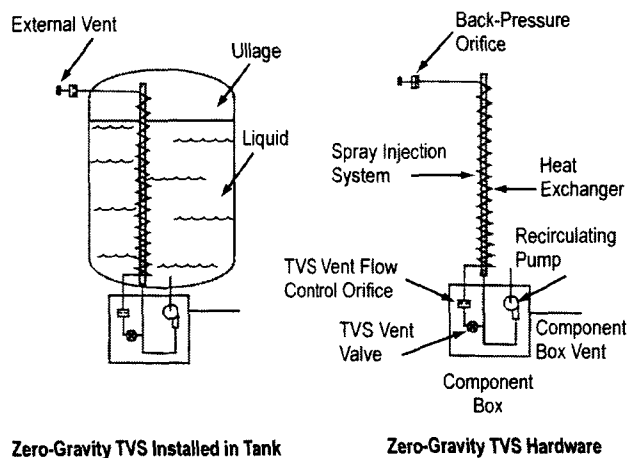

Zero-Gravity TVS Installed in Tank   Zero-Gravity TVS Hardware

FIGURE 1. TVS hardware configuration.

faster than the ullage pressure rise rate, the automated TVS operation logic was designed such that both the pump and the J-T valve operated simultaneously to reduce tank pressure as required.

THERMODYNAMIC VENT SYSTEM TEST SETUP AND PROCEDURES

Testing was performed at MSFC's East Test Area Thermal Vacuum Facility, Test Stand 300. The facility systems, in combination with the multipurpose hydrogen test bed's (MHTB's) shroud, enabled simulation of orbital environmental conditions. To accelerate the testing, the heaters were turned on. Then, boiloff testing was performed to determine the combination of ambient heat leak and heater input into the MHTB tank. This allowed setting up consistent initial conditions prior to each of the TVS tests. For each tank fill level, after the heat leak testing was completed, the tank was locked up and allowed to self-pressurize until the ullage pressure reached the maximum tank pressure set point. Upon reaching this pressure, both the recirculation pump and J-T valve were activated and mixing and venting commenced until the ullage pressure reached the minimum set point. At this point, the pump and the J-T valve were turned off, the tank was allowed to self-pressurize, and the automated operation cycle continued with a specified control band, typically ± 3.45 kPa. Detailed descriptions of the MHTB and the insulation system are provided by Martin and Hastings [4]. Detailed descriptions of LN_2 TVS testing and procedures are presented by Flachbart et al. [5].

MODEL OVERVIEW

Originally, the TVS performance computer program was developed to analyze LH_2 MHTB spray-bar TVS configurations. The TVS code is based on a transient one-dimensional analytical model and was formulated to characterize the MHTB TVS performance. The TVS performance formulation is comprised of four combined thermal-fluid models, including the heat exchanger, the spray manifold and injector tubes, the recirculation pump, and the tank. The heat exchanger model calculates the quality and two-phase pressure loss at the vent exit. The spray manifold and injection tube model determines the pressure drops within the manifold and tubes along with the spray flow rates and velocities leaving the injection orifices. The recirculation pump model calculates the pump head increase from the pump speed and the head coefficient curve provided by the pump manufacturer. The tank model is a lumped node model consisting of four control volumes—the ullage, tank wall, tank wall liquid, and bulk liquid. A detailed description of the TVS analytical model is given by Nguyen [6].

To utilize the TVS program for this LN_2 application, the original code was modified by incorporating LN_2 and gaseous nitrogen (GN_2) properties and LN_2 pump and J-T valve characteristics. Also, the tank model was modified by adding an additional heat source term, representing heater input and heat transfer through the legs to the bulk liquid control volume. Therefore, the total heat source represented the energy received by the bulk liquid via environmental heat leaks, heaters, and heat transfer through the MHTB's legs. The TVS analytical model is not provided here, since the major thrust of the current effort has been to correlate this analytical model/code with the MHTB test data.

RESULTS AND DISCUSSIONS

Two series of the LN₂ TVS tests were conducted in the summer of 2004. In the first series, the ullage consisted of only GN₂, while in the second test series, the ullage was comprised of a specified mixture of GN₂ and gaseous helium. In this paper, only the analysis and data correlation of the first series are reviewed. The second series analysis will be presented in the future. The first test series was performed at 90%, 50%, and 25% fill levels. All three tests were modeled using the TVS performance code. The total heat input was measured from boiloff tests. For each test, the total heat input into the system (environmental heat leaks + heat via legs + heat added by heaters) was ≈392 W. After the tank was locked up, the ullage pressure increased steadily until reaching a specified maximum set point; then, both the pump and vent were turned on. The pump and J-T valve were operated at nearly constant mass flow rates of about 1.5 kg/s and 0.025 kg/s, respectively. As the ullage pressure was reduced to the specified minimum set point, the pump and the vent were turned off. Since the ullage region is modeled as a single node by the TVS code, the predicted ullage temperature was compared to two ullage temperature measurements. These temperatures were measured by the closest sensor to the liquid-ullage interface—location 1, and the highest sensor in the ullage region—location 2. The TVS model predicted ullage pressure and temperature and bulk liquid saturation pressure and temperature were compared with the test data. Predictions by the TVS code, during the pressure rise mode, deviated from measured data; however, once the system entered the cyclic mixing/venting operational mode, the predicted values and measured data were in good agreement. In the following sections, detailed model predictions and comparisons for 90%, 50%, and 25% tests are discussed.

90% Fill Test

Correlations were performed for both the tank lockup and mixing/venting modes at 90% fill level. The maximum and minimum set points during this test were 127.6 kPa and 120.8 kPa, respectively. The ullage pressure comparison is depicted in FIGURE 2. For the lockup mode, the pressure rise rate was underpredicted by ≈12.5%. Average predicted and measured pressure rise rates were 0.21 Pa/s and 0.24 Pa/s, respectively. Between the mixing/venting cycles, the average ullage pressure rise rate was underpredicted by 16.7%. Average predicted and measured ullage pressure rise rates were 0.61 Pa/s and 0.733 Pa/s, respectively. During the depressurization, the model underpredicted the pressure drop rate by 33%. Average predicted and measured pressure drop rates were 4.4 Pa/s and 6.6 Pa/s,
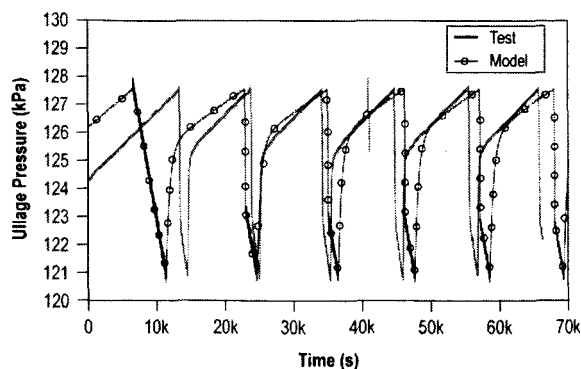

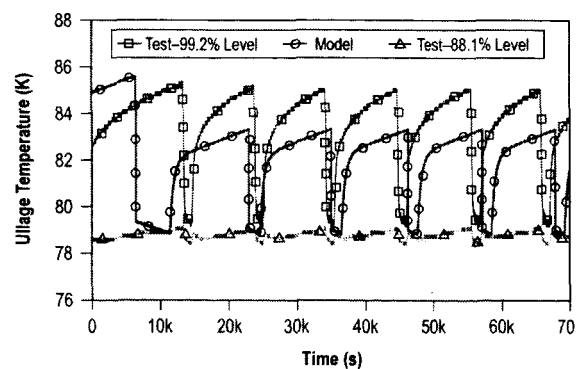**FIGURE 2.** Ullage pressure history, 90% fill level.

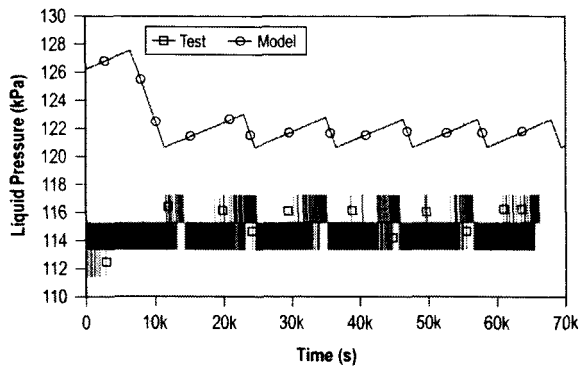**FIGURE 3.** Ullage temperature history, 90% fill level.

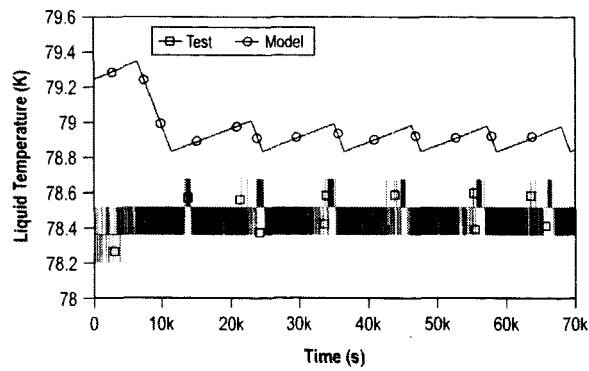**FIGURE 4.** Bulk liquid saturation pressure history, 90% fill level.

FIGURE 5. Bulk liquid temperature history, 90% fill level.

respectively. The model overpredicted the cycle duration by ≈17.2%. Average predicted and measured cycle durations were 3.4 hr and 2.9 hr, respectively. The predicted pressure rise rate deviation from the measured rate, particularly during the tank lockup mode, could be due to the oversimplification of the TVS model. It is believed that the analytical modeling, which assumed that the liquid and ullage were each represented by a single node, (1) did not accurately simulate the complex energy exchange occurring at the liquid-vapor interface, and (2) did not address stratification within ullage and liquid regions. The ullage temperature comparison, as shown in FIGURE 3, indicated a close agreement between the calculated and measured values. The average predicted and measured ullage temperatures were about 81 K and 83 K, respectively. Measured ullage temperatures of locations 1 and 2 were 79 K and 85 K, respectively. The predicted bulk liquid saturation pressure was compared with the test data, as shown in FIGURE 4. The bulk liquid saturation pressure was slightly overpredicted. The average predicted and measured bulk liquid saturation pressures were about 122 K and 115 kPa, respectively. As depicted in FIGURE 5, there was good agreement between the predicted and measured bulk liquid saturation temperature values. The average calculated and measured bulk liquid temperatures were about 78.9 K and 78.5 K, respectively.

50% Fill Test

Model correlations of test data were performed for the tank lockup and mixing/venting modes at 50% fill level. The maximum and minimum set points during this test were 124 kPa and 118 kPa, respectively. The ullage comparison is illustrated in FIGURE 6. For the tank lockup period, the model overpredicted the ullage pressure rise rate by 19.3%. Average predicted and measured pressure rise rates were 0.37 Pa/s and 0.31 Pa/s respectively. However, between mixing/venting cycles, the average pressure rise rate was underpredicted by 9.5%. The average predicted and measured ullage pressure rise rates were 0.57 Pa/s and 0.63 Pa/s, respectively. During the mixing/venting period, the pressure drop rate predicted by the model was nearly the same as the test data value (≈4 Pa/s). The cycle duration was underpredicted by ≈8.4%. Average predicted and measured cycle durations were 2.82 hr and 3.08 hr, respectively. Similar to the 90% fill level case, the predicted pressure rise rate deviated from the measured rate, particularly during the tank lockup mode. However, once the system entered the cyclic mixing/venting operational mode, the ullage region became destratified; therefore, the calculated ullage pressure was in good agreement with measured data. As shown in FIGURE 7, the calculated and measured ullage temperatures were in very good agreement. The average
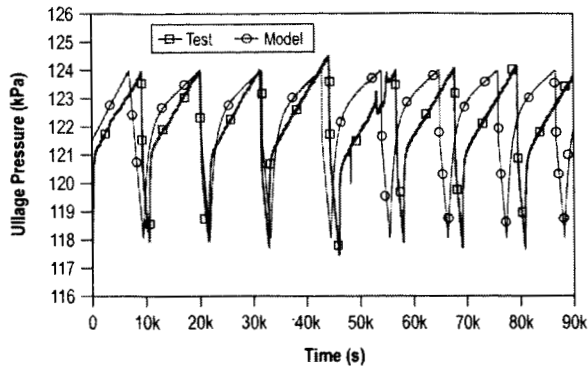
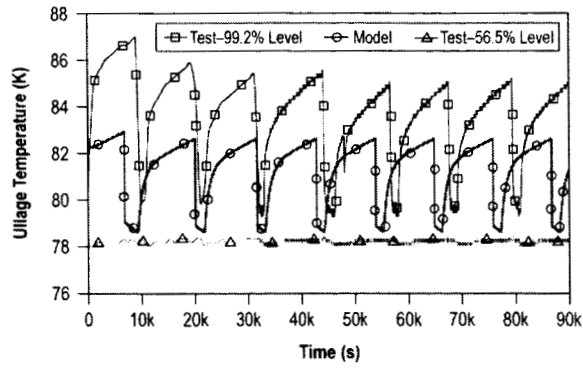**FIGURE 6.** Ullage pressure history, 50% fill level.

FIGURE 7. Ullage temperature history, 50% fill level.
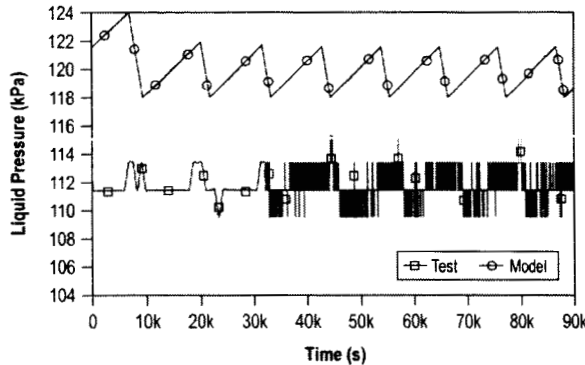

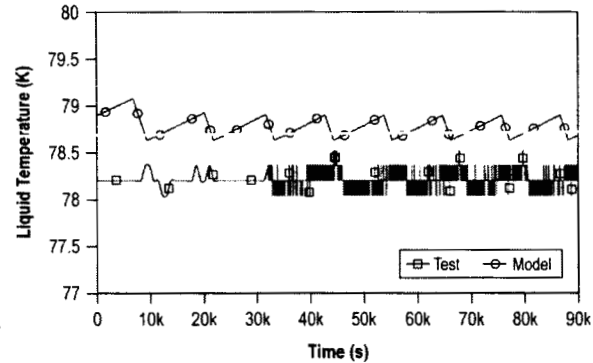**FIGURE 8.** Bulk liquid saturation pressure history, 50% fill level.

FIGURE 9. Bulk liquid temperature history, 50% fill level.

predicted and measured ullage temperatures were about 80.5 K and 80.55 K, respectively. Average measured ullage temperatures at locations 1 and 2 were 78.1 K and 83 K, respectively. FIGURE 8 shows that the bulk liquid saturation pressure was slightly overpredicted. The average predicted and measured bulk liquid pressures were 120 kPa and 112 kPa, respectively. Comparison of the bulk liquid temperature, as depicted in FIGURE 9, indicated good agreement between the predicted and measured values. The average predicted and measured bulk liquid temperatures were 78.7 K and 78.2 K, respectively.

25% Fill Test

Correlations were conducted for the lockup and mixing/venting modes at 25% fill level. The maximum and minimum set points during this test were 124 kPa and 118 kPa, respectively. The ullage pressure comparison is illustrated in FIGURE 10. For the lockup mode, the ullage pressure rise was overpredicted by ≈41.8%. Average predicted and measured pressure rise rates were 0.61 Pa/s and 0.43 Pa/s, respectively. Between mixing/venting cycles, the ullage pressure rise rate was slightly overpredicted by 7%. Average predicted and measured ullage pressure rise rates were 0.75 Pa/s and 0.7 Pa/s, respectively. During the mixing/venting period, the pressure drop predicted by the model was nearly the same as the test data value (≈4.3 Pa/s). The cycle duration was underpredicted by 5%. Average predicted and measured cycle durations were 2.5 hr and 2.63 hr, respectively. Similar to the previous cases, the predicted pressure rise rate deviated
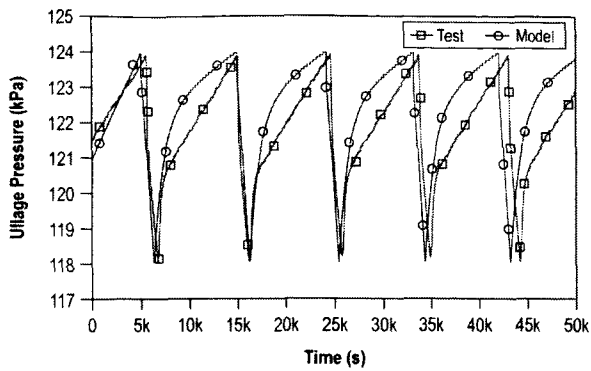
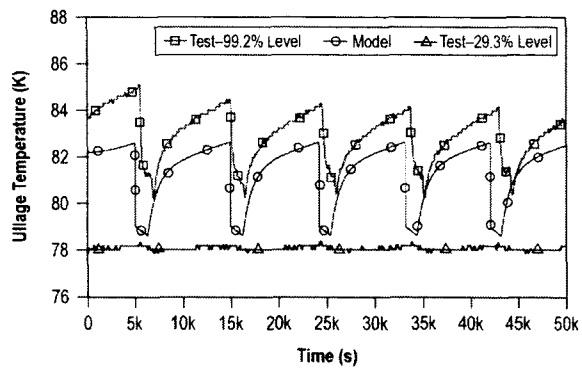FIGURE 10. Ullage pressure history, 25% fill level. FIGURE 11. Ullage temperature history, 25% fill level.
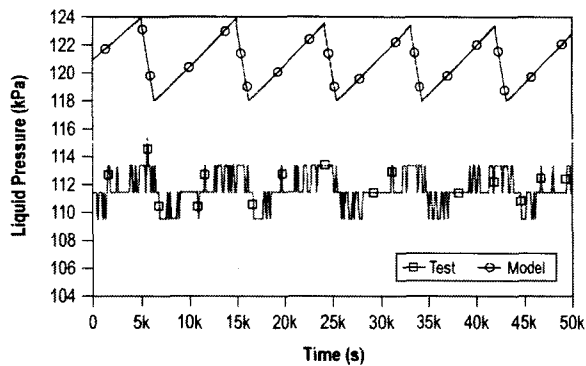

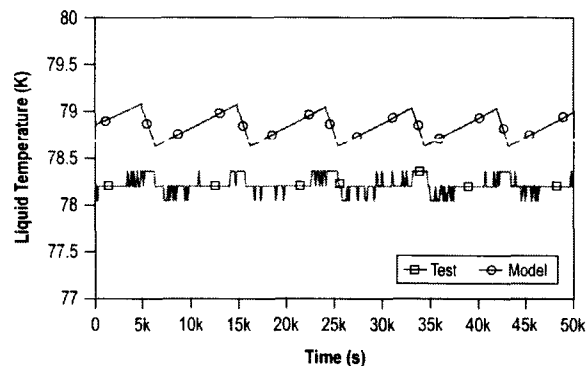FIGURE 12. Bulk liquid saturation pressure history, 25% fill level. FIGURE 13. Bulk liquid temperature history, 25% fill level.

from the measured rate but as the system entered into the mixing/venting operational mode, the prediction was in good agreement with the data. The ullage temperature comparison, as shown in FIGURE 11, indicated very good agreement between the predicted and measured values. The average predicted and measured ullage temperatures were about 81 K and 80.5 K, respectively. Average measured ullage temperatures at locations 1 and 2 were 78.2 K and 83 K, respectively. As shown in FIGURE 12, the predicted saturated bulk liquid pressure was slightly overpredicted. Average predicted and measured bulk liquid pressures were 121 kPa and 112 kPa, respectively. The bulk liquid temperature comparison is shown in FIGURE 13. The comparison indicated very good agreement between the predicted values and those of test data. The average measured and predicted bulk liquid temperatures were 78.2 K and 78.8 K, respectively.

SUMMARY

After modifying the LH₂ MHTB TVS configuration, several LN₂ TVS tests were conducted for 90%, 50%, and 25% fill levels. To accelerate the testing, heaters were installed in the lower section of the tank. For each tank fill level, after boiloff testing was completed, the tank was locked up and allowed to self-pressurize until the ullage pressure attained the maximum tank pressure set point. Upon reaching this pressure, both the recirculation pump and J-T valve were activated and mixing and venting continued until the ullage pressure reached the minimum set point. After the pump and the J-T valve were

turned off, the tank was allowed to self-pressurize, and the automated operation cycles continued within the specified control band. The original one-dimensional LH_2 MHTB TVS performance program was modified for the LN_2 TVS configuration. Using this modified TVS code, ullage pressure and temperature and saturated bulk liquid pressure and temperature were calculated and correlated with corresponding measured parameters. Correlations between the modeled and measured data were conducted for 90%, 50%, and 25% fill level tests. For the tank lockup mode, the ullage pressure rise rate predictions were within 12.5%–41.8% of test data. Between mixing/venting cycles, the ullage pressure rise rate predictions were within 7%–16.7% of measured data. For the mixing/venting mode, the predicted ullage pressure drop rate was 33% lower than the measured value for 90% fill level, while the ullage pressure drop rates for 50% and 25% fill levels were similar to test data. The predicted cycle durations were within 5%–17.2% of measured values. The ullage temperature predictions were within test values.

Although the predicted pressure rise rates deviated from measured values, the ullage pressure drop rates correlated very well during the mixing/venting cycles. It is believed that the analytical modeling, which assumes that the liquid and ullage are each represented by single nodes, did not simulate the complex energy exchange occurring at the liquid-vapor interface. With mixing, the stratification effects are minimized and the energy exchange across the liquid surface is more predictable; therefore, the analytical and measured data closely matched. The correlations for the bulk liquid saturation pressure and temperature indicated relatively good agreement for the entire range of conditions tested.

ACKNOWLEDGMENTS

REFERENCES

1. Hastings, L. J., Flachbart, R. H., Martin, J. J., Hedayat, A., Fazah, M., Lak, L., Nguyen, H., and Bailey, J. W., "Spray Bar Zero-Gravity Vent System for On-Orbit Liquid Hydrogen Storage," *NASA/TM—2003–212926*, October 2003.
2. Flachbart, R. H., Hastings, L. J., and Martin, J. J., "Testing of a Spray Bar Zero Gravity Cryogenic Vent System for Upper Stages," AIAA 99–2175, *35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Los Angeles, CA, June 20–24, 1999.
3. Lak, T., and Wood, C., "Zero-G Thermodynamic Vent System Final Report," Rockwell Aerospace Report No. SSD 94M0038, Contract No. NAS8–39202, 1994.
4. Martin, J., and Hastings, L., "Large-Scale Liquid Hydrogen Testing of a Variable Density Multilayer Insulation With a Foam Substrate," *NASA/TM–211089*, June 2001.
5. Flachbart, R. H., Hastings, L. J., Hedayat, A., Nelson, S. L., and Tucker, S. P., "Testing of a Spray-Bar Thermodynamic Vent System in Liquid Nitrogen," Paper C1–G–05, CEC2005, in *Proceedings of Advances in Cryogenic Engineering*, to be published.
6. Nguyen, H., "Zero-G Thermodynamic Venting System (TVS) Performance Prediction Program," Rockwell Aerospace, Contract No. NAS8–39202, May 24, 1994.