Densification of Liquid Oxygen – A Comparison of Numerical and Experimental Results

J. Sasson[1], A.F. Skaff[1], M.L. Meyer[2], D.L. Rios[3], T.Y. Hui[1]

[1]Sierra Lobo, Inc., USA
[2]NASA Langley Research Center, USA
[3]NASA White Sands Test Facility, USA

ABSTRACT

The NASA Launch Services Program and the NASA Engineering Safety Center had a requirement to conduct large scale tests with densified liquid oxygen. A densification system was designed where two dewars were simultaneously filled with liquid oxygen and pumped down with an ejector using nitrogen as the motive gas to densify the liquid. The dewars were evacuated to a final pressure of 5.86 kPa. The temperature of the liquid was not measured. Three distinct numerical models were created and compared against the experimental results. While these models were able to predict the final pump down time to within 15 %, the transient behavior agrees with the experimental results within 30%. The final predicted temperature could not be verified as this was not measured during the experiment.

INTRODUCTION

In 2017, the NASA Launch Services Program (LSP) and the NASA Engineering Safety Center (NESC) had a requirement to conduct large scale tests with densified liquid oxygen (DLO2). Sierra Lobo, Inc. (SLI) was contracted to design and deliver a densification system. The project had a very short schedule, with a goal of beginning operations within eight months of authority to proceed, in order for the test results to have maximum impact for the Launch Services Program. This schedule pressure was heavily weighted in many decisions, including those affecting the design of the LO2 densification system. After evaluating several potential facilities for the test operations, the NASA White Sands Test Facility (WSTF) Area 250 was selected as it had some existing and relevant infrastructure, sufficient space for the additional required systems, and, importantly, was available to begin design and construction immediately. This report will discuss the oxygen densification system requirements, the design of the system to meet those requirements, and finally will compare performance of the system predicted by the evaporative cooling models to actual performance of the system during operations at Area 250.

EXPERIMENTAL SETUP

The critical requirements for the DLO2 system were the temperature of the liquid oxygen, the quantity of liquid oxygen required for a test, the flow rate required to be discharged from the DLO2 system, and the frequency of testing. For this test program, the liquid oxygen had to be flowed through over 46 m (150 feet) of pipe to reach the test article, and given the schedule and budget requirements the pipe could not be vacuum jacketed. It was also necessary to flow the DLO2 rate a rate of at least 1166 liters per min (lpm) (308 gallons per minute (gpm)), with a goal of 1325 lpm (350 gpm). A 7.62 cm (3 inch) diameter tube was selected for the transfer line to minimize the pressure losses in the pipe at these flow rates. A wrapped aerogel-based insulation was used on the transfer pipe to reduce heat load to the flowing LO2. The heat load in the system was estimated and determined that the DLO2 supply needed to be held below 65 K to meet the requirements at the test article delivery point. In addition, each test would require a total of approximately 11,400 liters (3000 U.S. gallons) of DLO2. Finally to address the project's primary data needs, it would be necessary to test 2 or 3 times per week.

Dewar

The main element of the densification system was the dewar in which to produce and store the DLO2. Options considered ranged from existing vessels to procuring a new dewar designed to this tests requirements. Several aspects of the test requirements were challenges for use of existing vessels. First, outflow rate is higher than typically designed into a dewar. Second, most LO2 dewars are not designed for, or certified to, operating temperatures below liquid nitrogen normal boiling point (77 K) and the DLO2 would be produced to below 65 K. The vessels are not typically intended to have vacuum pulled on the stored fluid, and last, the high outflow rate required for this test is unusual. Initially, a 34,000 liter (9000 U.S. gallon) dewar existing at Area 250 was evaluated. Unfortunately, the dewar would have required significant modification to meet the outflow rate requirement. Next, the option to procure a new dewar was considered. This was the most ideal option and appeared feasible, although some schedule risk was present. It was also a significant investment in a tight budget. The selected approach utilized two 19,000 liter (5000 gallon) ISO dewars built by WesMor Cryogenics. These were borrowed from the NASA Kennedy Space Center and safe use for this application required some special operational controls. The Wesmor LO2 dewars had a manufacturer rating of 77.6 K (-320 °F) minimum and 1.325 MPa (180 psig) maximum allowable working pressure (MAWP), which was de-rated to 0.77 MPa (100 psig) for DLO2 operations. They were categorized as an accessed hazard exclusion when operated at below the minimum rating pressure and above WSTF Ambient internal pressure (0.085 MPa (12.3 psia)). i.e. personnel could not be near the dewars when operated below their rated temperature and with positive ullage pressure. Another operational challenge due to use of a existing dewars was that they did not have internal fluid temprature instrumentation to monitor either progress of the densification process or potential development of thermal stratification in the LO2.

Ejector

Several options for the LO2 densification process were evaluated against the requirements. First was a continuous flow shell-and-tube heat exchanger using liquid nitrogen as the heat exchange fluid, however the flow rate and need for below normal boiling point LN2 made this option impractical. This drove the design trade to a batch production process. Three main batch production options were considered.

1. Use of an existing helium refrigeration system previously used by NASA to demonstrate preventing boil-off loss and lowering temperature of a large liquid hydrogen dewar (Reference 1).
2. Use evaporative cooling of LO2 stored in a dewar by reducing the ullage pressure above the liquid.
    a. Option 2A: Use a large oxygen-compatible mechanical vacuum pump to reduce the dewar ullage pressure.
    b. Option 2B: Use a gas driven ejector pump to reduce the dewar ullage pressure.

Although the helium refrigeration system was able to reduce temperature in a 33,000 gallon LH2 dewar in prior testing, it was undersized for the quantity of liquid oxygen in this test and the frequency of testing required, and it required an additional heat exchanger for the stored LO2. The two evaporative cooling options evaluated as practical. WSTF Area 250 had both sufficient electrical power available for the mechanical vacuum pump and a large gaseous nitrogen supply to serve as the motive fluid for an ejector-based system. Either option could be built with capacity to densify more than two times the quantity required for a single test in a two day period. However, the timeline for procuring the two systems differed significantly, and the ejector based system was selected based on schedule, even though the cost of operating it was higher – this system was intended to be used for a single test campaign, so operating costs were weighted lower than schedule.

In the selected design, a single ejector pumps down the ullage of both tanks simultaneously. The ejector used in this experiment was a two-stage ejector manufactured by Croll-Reynolds. A schematic of this ejector is shown in Figure 1. This ejector uses nitrogen at 400 psia and atmospheric temperature as the motive fluid. Motive fluid flowed only through the first stage (ejector Y) at 219 scfm when the ullage pressure was above 2.5 psia. The second stage (ejector Z), was used in conjunction with first stage to evacuate the ullage when the pressure was under 2.5 psia. Both stages combined used a total of 1,423 scfm of nitrogen. The pump down rate of the ejector depended on the ullage pressure and temperature. A pump down curve (suction flow rate versus suction pressure) was provided by the manufacturer for oxygen gas at a specific constant temperature (116.5 K). This curve was used in the thermodynamic model, and the mass flow rate was corrected for ullage temperature at each time step. The pump down curve at 116.5 K is shown in Figure 2. The figure shows the suction flow rate as a function of ullage (suction) pressure.

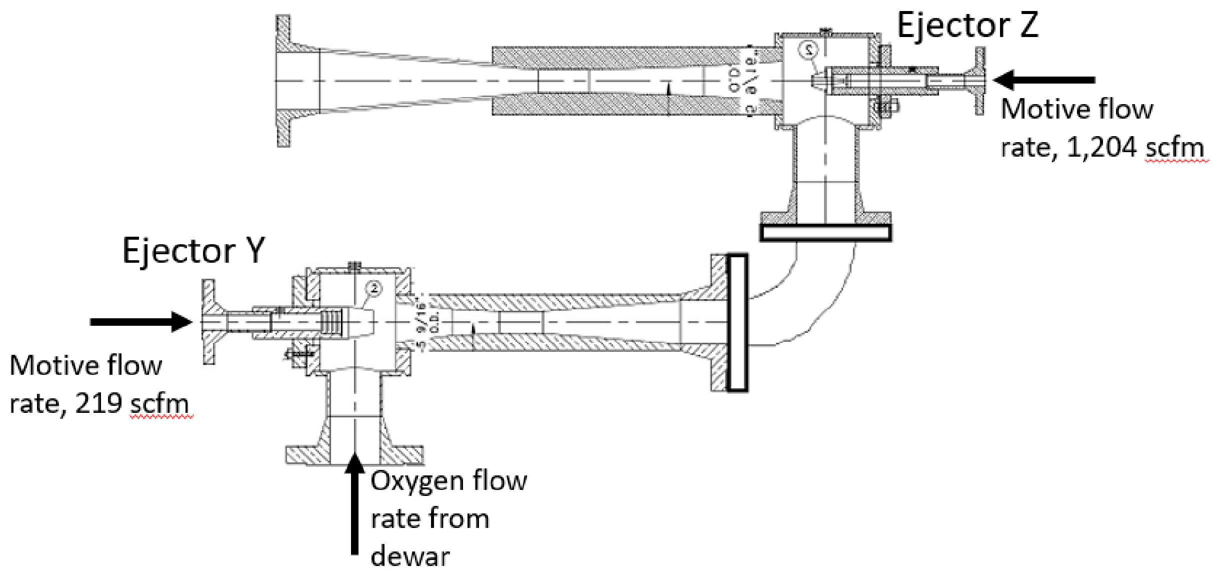


Figure 1: *Pump down ejector setup.*

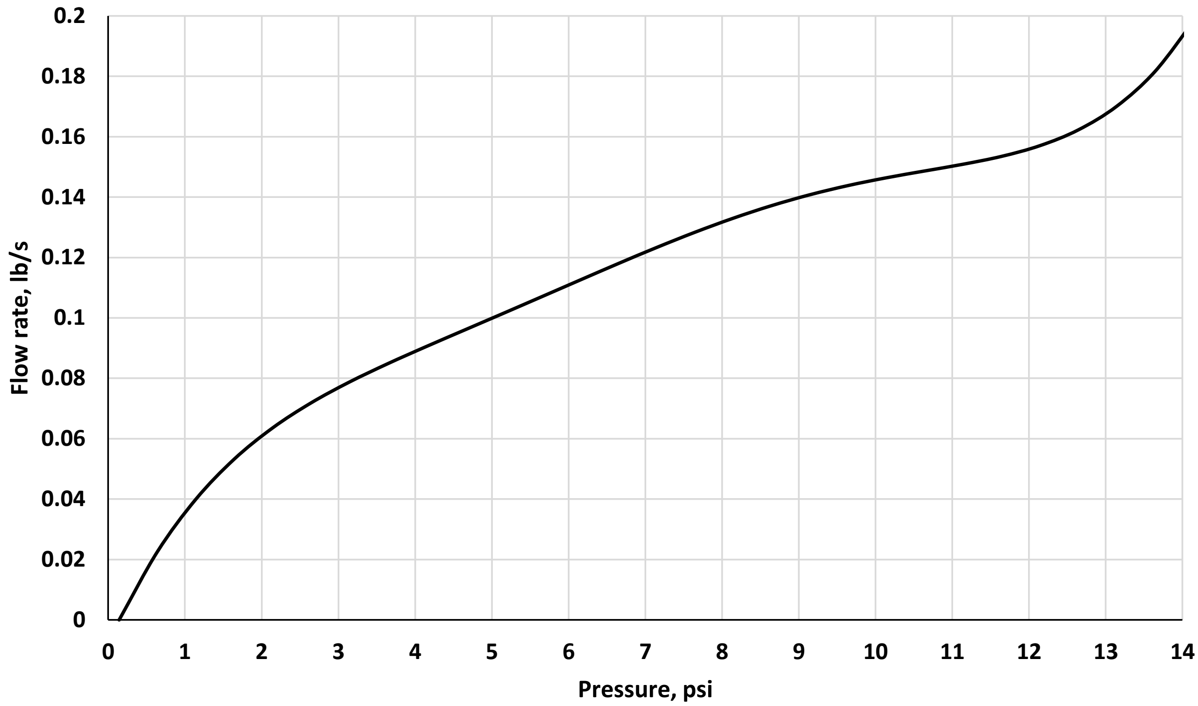


Figure 2: *Pump down ejector curve.*

OPERATION

The integrated DLO2 system design shown in Figure 3 was selected based on project cost and schedule. The system used the vacuum ejector pump to pull vacuum on the two LO2 ISO dewars, in order to achieve the required LO2 temperature and density, and used gaseous oxygen supplied from a 41.45 MPa (6000 psig) GO2 tube bank to provide up to 0.77 MPa ullage pressure to drive the required DLO2 flowrates. The ejector pump was supplied with 3000 psig WSTF facility GN2 drive pressure that was regulated to 400 psig. The ejector-based puming system was assembled on a skid, which was located between the two DLO2 dewars, is shown in Figure 4.

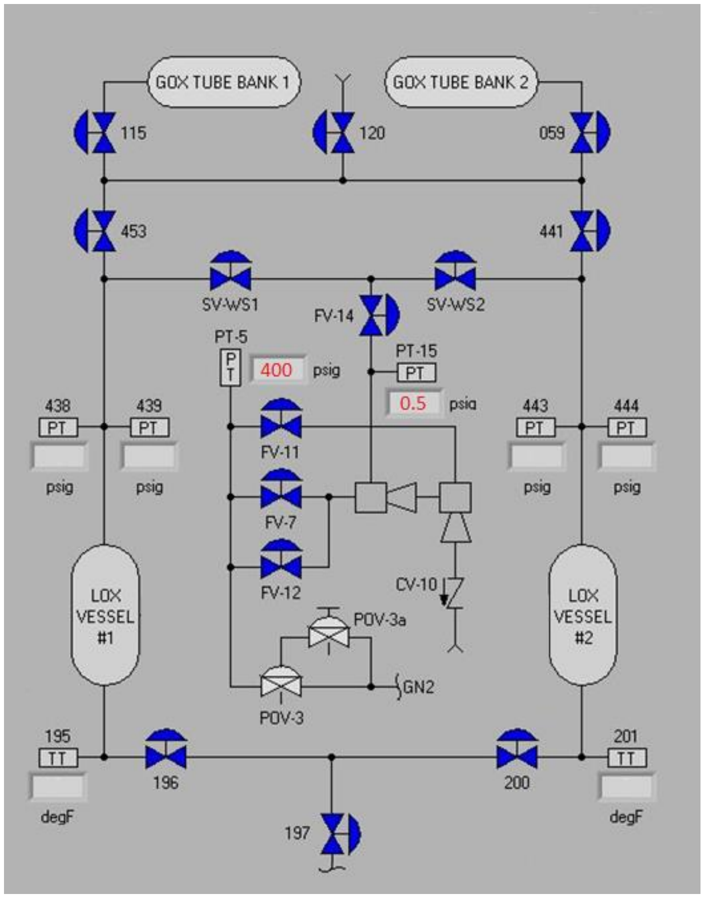


Figure 3: *LOX Densification system schematic.*

The densification process required 24 hour operations in order to achieve the required vacuum pressure of approximately 0.5 psia. A mixing operation was performed when the pressure would reach approximately 1.0 psia to prevent stratification of the DLO2 in the dewars. In order to perform this operation, pressurized GO2 was used to pressurize the ullage of one dewar while the ejector pump continued to pull vacuum on the second one. Once the second dewar was full the process was reversed until the level of both dewars was equal. The densification process would then continue by isolating the GO2 push pressure, venting the ullage pressure and continuing to pull vacuum on both dewars until the start of testing. Figure 3 depicts a typical densification operation with vacuum pressure on the LO2 dewars being monitored by PT-15/22 (psia) and the temperature of the DLO2 during the mixing operations was read by TT-195/23 (°F) and TT-201/24 (°F). At initiation of a test, the ejector pump was isolated and the ullage of the LO2 dewars was pressurized with GO2 to the required push pressure and then the LO2 delivery remote isolation valve would be opened to supply the test article at the desired fill rate.

As noted above, the ejector pump which was designed by SLI was fed from facility gaseous nitrogen system. This required additional LN2 offloads at the WSTF GN2 generation facility to supply both the required drive gas for the ejector pump and normal WSTF facility operations. The 3000 psig GN2 facility drive pressure was consumed at a rate of approximately 2574 (70 inches/day) gallons per day; typical densification operations were performed for about 36 hours. Table 1 shows the typical LO2 dewar levels at different points during the pretest densification operation, including losses due to the densification process.

Figure 4 *Ejector between WesMor DLO2 dewars.*

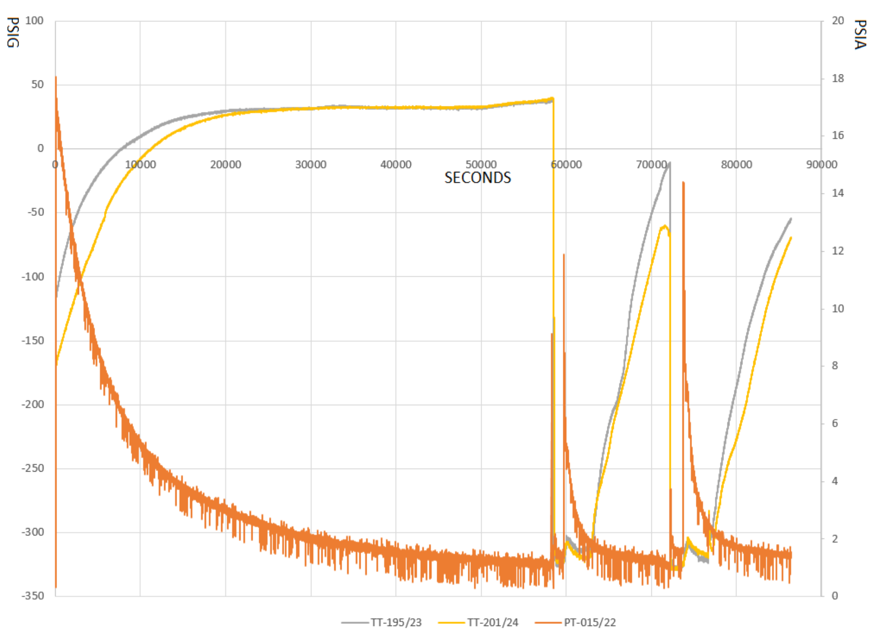


Figure 5: *Typical LO2 densification data.*

Table 1: *Typical liquid oxygen levels at different points during the densification process.*

LO2 Dewar #1	LO2 Dewar #2	Comments

41”	2096 gallons **	42”	2167 gallons**	Initial LOX Levels
35”	1675 gallons **	37.5”	1864 gallons **	Densified LOX Levels
10”	280 gallons **	15”	482 gallons **	Post Test Densified LOX Levels
-	1395 gallons	-	1382 gallons	Densified LOX used for test (2777 gallons)

** At WSTF Ambient 12.3 psia

NUMERICAL MODELS

A thermodynamic model of the ejector pumping down on the ullage of the liquid oxygen dewar was created. The purpose of the model was to determine the required time to reach a specific ullage pressure using the ejector. The motivation for pumping down the tank was to evaporatively cool the liquid oxygen to the lowest possible saturation temperature without solidifying the oxygen. Various thermodynamic models were created: a control volume model, a single node model in Thermal Desktop, and multi-node model also in Thermal Desktop.

Assumptions

Each model was compared only against the first cycle of densification as shown in Figure 5. Since the liquid or ullage temperatures in the dewar were not measured, comparing the model results against experimental data after mixing would result in increased uncertainty. The initial conditions are then the ones at time equal zero based on Figure 5. The temperatures shown in Figure 5 (TT-195, TT-201) are the liquid temperature in the transfer line between the two dewars and are only indicative of densification progress during a mixing cycle. The initial conditions for all three models are summarized in the list below.

Initial conditions:

1. Initial liquid fill level: 7.93 m^3
   - Ullage level: 58.1%
2. Initial ullage pressure: 116 kPa (16.83 psia)
3. Initial liquid temperature: 91.5 K (-294.97 °F) (saturation temperature at initial pressure)
4. Ullage and liquid temperature are equal (assumption)

Based on the initial conditions, the fluid is assumed to be a saturated mixture with a quality of 0.006 at the start of the densification process. Various other assumptions also apply to all three different models. First, the heat leak, $\dot{Q}_{in}$, is 122 W and is provided by the dewar manufacturer. This heat leak value was not independently verified. This is assumed to be the only source of heat into the models. The insulation, vacuum level in the vacuum jacket, and atmospheric conditions are therefore not taken into account in these models. The heat leak from the dewar is applied evenly across all of the nodes.

Second, the vapor flow rate out of the ullage is only a function of ullage pressure and temperature. Flow restrictions (such as valves, reducers, bends, etc.) upstream or downstream of the ejector are assumed to be negligible. These components would not significantly affect the results, but would drastically increase the run time of the models. Further details on the thermodynamic effects of these restrictions are shown in a subsequent section. The pump curve provided by the ejector manufacturer assumes that the oxygen ullage vapor is at 116.5 K (-250 °F). The effect of temperature was taken into account by multiplying the flow rate at a given pressure by the following ratio.

$$\sqrt{\frac{T_{ref}}{T}}$$

Where T_{ref} is the temperature at which the pump down curved is was determined, and T is instantaneous calculated ullage temperature. The ratio of temperatures was derived through conservation of mass. A curve fit on the graph shown in Figure 2 is used to determine the pump down rate. The resulting curve fit with the temperature correction is a fifth order polynomial in terms of pressure multiplied by the previous temperature ratio. Heat leak through the ejector was also assumed to be negligible.

Control Volume Model

A simple control volume model was created to quickly estimate the time required to pump down the ullage to approximately 6.9 kPa (1.0 psia). This model is easily implemented and initial conditions, as well as design parameters, can quickly be varied. The control volume is shown in Figure 6. The vapor and liquid are assumed to be at equilibrium at all times, and thus at the same temperature. The entire volume is treated as a saturated mixture. Energy transfer between the liquid and vapor interface is assumed to be zero. The ullage pressure drops as vapor (and therefore mass) exits the ullage through the ejector. This drop in pressure results in a drop of temperature. The resulting pressure reduction and heat leak results in a small amount of boil-off. The mass balance is shown in Figure 6 as well. The boil-off as well as the increase in liquid density results in a decrease of liquid level. Since the mixture is not assumed to be stratified, the temperature change across the entire fluid mass is assumed to be instantaneous. The change of mass, and temperature are described by equations governing conservation of mass and energy.

(1)

$$\frac{\mathrm{d}m_f}{\mathrm{d}t} = -\dot{m}_v$$

$$\frac{d\mathrm{m_g}}{d\mathrm{t}} = -\dot{m}_e + \dot{m}_v$$

(2)

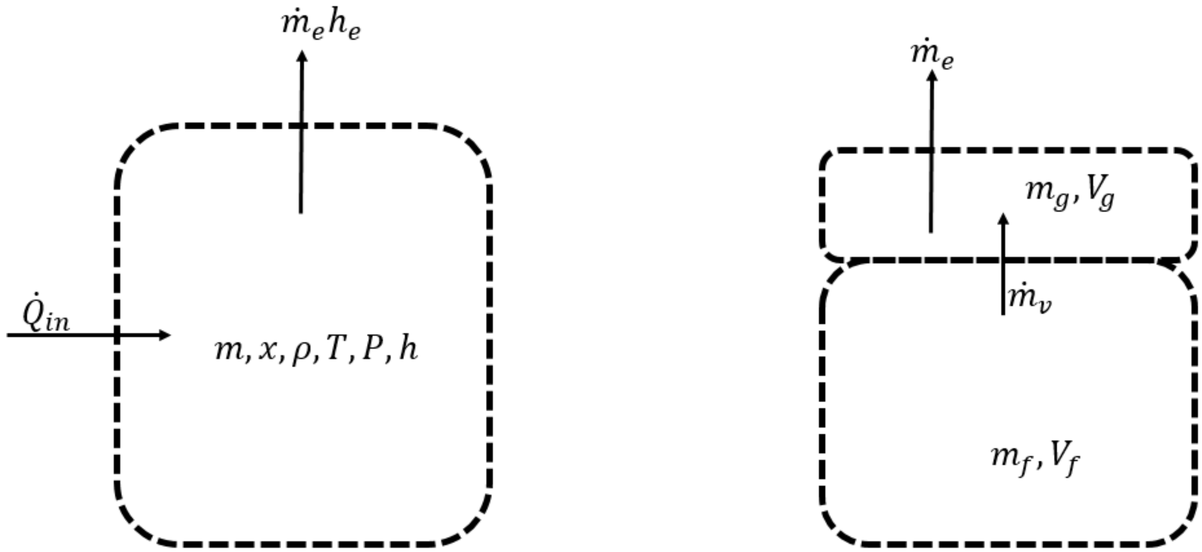
$$\frac{\mathrm{d}h}{\mathrm{d}t} = \dot{Q}_{in} - \dot{m}_e h_e$$

$$x = \frac{h - h_f}{h_g - h_f} = \frac{m_g}{m_g + m_f}$$

$$P = P_{sat}(x, h)$$

Equations 2, 3, and 4 are differential equations that describe the instantaneous mass and enthalpy of the system. In Equations 1 and 2, $\dot{m}_v$, is the liquid mass evaporated due to boil-off. Decrease in pressure and heat addition both contribute to the boil-off. This termed is defined in Figure 2. The liquid mass evaporated leaves the liquid control volume, and equals the vapor mass increase in the ullage due to boil-off. This flow rate is assumed to be small compared to the ejector flow rate. Equation 3 depends heat leak into the dewar as well as the ullage enthalpy, h_e. This enthalpy is assumed to be equal to the saturated vapor enthalpy of the mixture at the instantaneous pressure, h_g. Equation 5 describes the quality of the system, and relates the enthalpy to the vapor mass of the system.

Given the set of initial conditions previously described, the three differential equations can be solved simultaneously using the Fourth Order Runge Kutta technique. The system of equations is solved in Fortran. The details of the numerical scheme are found in Reference 2. Equations 1 and 5 are used to determine the ejector mass flow rate and quality, respectively. The pressure used to calculate the ejector mass flow rate is the saturation pressure based on quality and enthalpy. This is calculated by an equation of state using the REFPROP subroutines [3]. All other fluid properties are also calculated using REFPROP.



$$m = m_f + m_g$$

$$\dot{m}_v = \frac{\dot{m}_f - \dot{m}_{f,i-1}}{\Delta t} = \frac{\dot{m}_g - \dot{m}_{g,i-1}}{\Delta t}$$

Figure 6: *Control volume (left) and mass balance (right) for control volume model.*

Thermal Desktop Models

A one node Thermal Desktop model was also created to compare the results of control volume model. In this case, the fluid is modeled a single lump (time dependent lump or tank), however the ullage is assumed to be at a different temperature than the liquid. In this case Thermal Desktop solves two energy equations simultaneously; one for the liquid volume and another one for the ullage. This model also takes into account the energy transfer between the liquid and vapor interface. The heat leak is directly applied to the lump. The ejector is modeled as a set flow rate path, where the flow rate is the ejector pump down curve fit.

The multi-node Thermal Desktop model is a simplified version of the stratified tank model created by CRTech. This model uses a core model to define the fluid is no boundary layer existed combined with a boundary layer model to account for the fluid recirculating through the thermal boundary layer developed. The following is a brief summary of the model. Further details are found in Reference 4.

The core fluid is modeled by a flat front approach. This ideal core model is a stack of constant volume tanks containing liquid that represent stratification within the liquid, and another stack of constant volume tanks containing vapor representing stratification within the ullage volume. All of the tanks are twinned tanks that will separate to liquid/vapor parts as the liquid level decreases. Only one of the tank lumps is split in a two-phase mode at a particular time. The rest are in a homogeneous state containing a single phase.

The boundary layer model assumes that the mass flow rate added to a turbulent boundary layer for natural convection flows can be approximated as a simple function of the local heat transfer from the wall as shown by Ring in Reference 4.

$$\dot{m}_{BL} \approx \frac{4\,UA}{c_p}$$

Where *UA* is the heat transfer coefficient multiplied by the heat transfer are for the segment, and c_p is the specific heat capacity of the fluid at constant pressure. As the boundary layer grows, each segment extracts this approximate flow rate from the core until the temperature of the core fluid is warm enough to cease the rise of the boundary layer. For the liquid boundary layer, this process continues until the last liquid tank is reached. The remaining boundary layer flow will enter the liquid tank at the surface. Since the top layer of liquid is colder than the ullage, the boundary layer forms at the top of the dewar, and flows to the bottom most vapor tank.

The boundary layer is modeled by using junctions joined by SetFlows connectors built in parallel to the core fluid. A set of STUBEs connect the core lumps for the boundary layer junctions. The low flow resistance maintains the boundary layer junctions and the core lumps at the same pressure. Since the junctions have no volume, the boundary layer is assumed to be thin, especially compared to the core volume. Therefore the boundary layer thickness is not actually calculated.

To reduce run time, the model uses only 20 nodes. The dewar is divided into 20 equally spaced sections, and the volume of each fluid lump varies with height. The dewar wall is also included in this model. This is different from the CRTech model as the model of each fluid lump is constant. The model in this investigation also has a constant heat leak, and it is not dependent on ambient conditions and insulation properties. The fill portion of the experiment is also not modeled as in the CRTech model. The heat leak value, $\dot{Q}_{in}$, is applied directly to the tank walls, and it is distributed equally among all the nodes.

RESULTS AND DISCUSSION

The experimental pressure profile is shown in Figure 7. The second stage of the ejector was used after approximately 7 hours. The transition in using both ejectors was smooth, as no change in the pump down rate can be detected when the second stage comes online. The time to reach 1 psia was approximately 15 hours. After this, the fluid in both tanks is mixed to avoid stratification, resulting a small increase in pressure. The final pressure was 0.85 psia. This pressure profile is the one seen in Figure 5.

The model results are compared to the experimental results in Figure 7 which shows the dewar pressure for the experiment, and all three models. The results from the control volume model and the single lump Thermal Desktop model show very little difference, even though the single lump Thermal Desktop model had a different temperature for both the ullage and the liquid. The two results had a maximum deviation of 20%. These results show a maximum deviation of 28% with the experimental results at any given time.

The multiple lump model in Thermal Desktop has better agreement with the experimental results than the previous two models (control volume and single node Thermal Desktop). As shown in Figure 7, the maximum deviation for the multiple lump model from the transient behavior is 18%. The multiple lump model predicts the time to reach 1 psia within 20%. The model also shows some degree of stratification in the dewar. The temperature has a small variation with height at when the pressure reaches 6.98 kPa. The variation of temperature between the top and bottom is 7 K, with the maximum temperature at the bottom of the dewar. This variation cannot be verified with the experimental results as it was not measured.

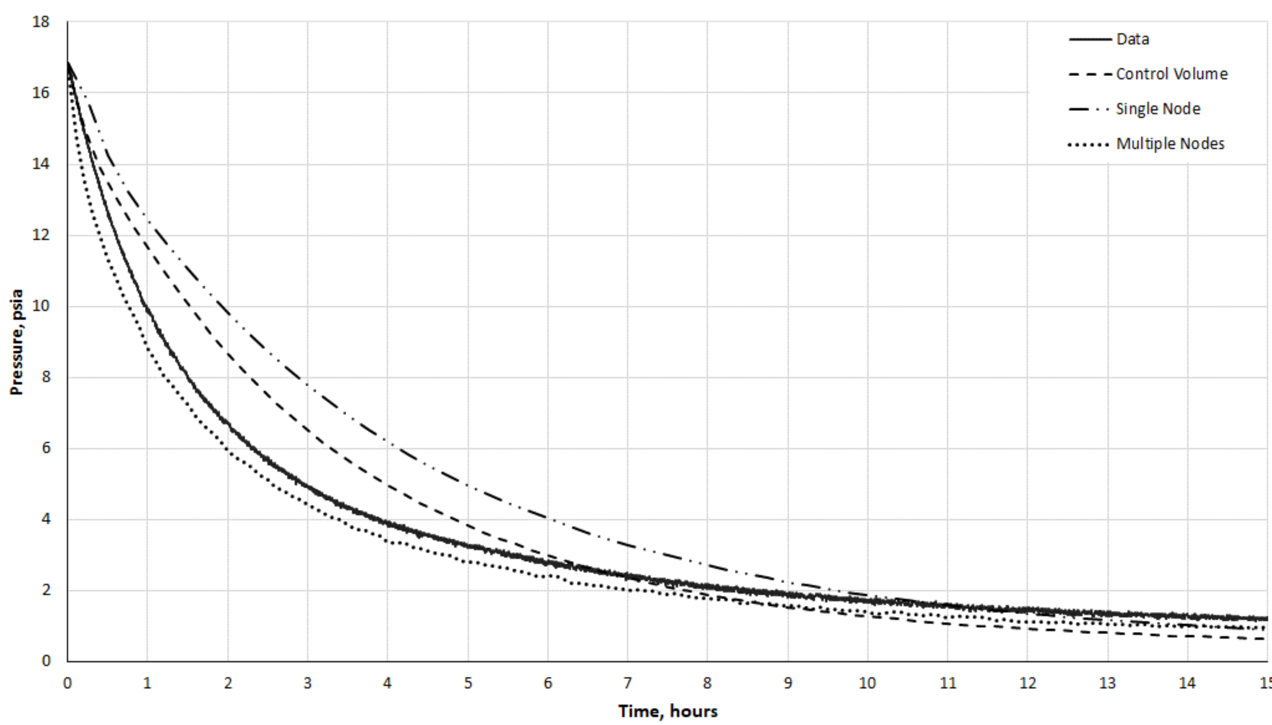


Figure 7: *Pump down results.*

CONCLUSION

Liquid oxygen was densified using using evaporative cooling with an ejector pump using high pressure nitrogen gas as the motive fluid. The ejector was connected to two dewars at approximate the same liquid level and initial pressure. The ullage on the dewars was pumped down until a final pressure of 5.86 kPa (0.85 psia) was reached. The ullage pressure was recorded every 10 seconds. The pump down was modeled three different ways, and the results were compared against the experimental results. These numerical models were able to approximate the time required to pump down to approximately 6.9 kPa (1 psia) within 20. While the model results are encouraging, this experiment does not meet the requirements of a validation experiment. In order to do so, it needs to incorporate fluid and wall temperatures at various points in the dewar, and measure the suction flow rate. All of these are necessary to verify the accuracy of the mathematical models. However, the methodology proved sufficiently effective for design of a system for the large scale LO2 densification required in this experimental setup.

REFERENCES

1. Notardonato, W. U., "Final Test Results for the Ground Operations Demonstration Unit for Liquid Hydrogen", *Cryogenics*, Volume 88, 2017, pp. 147-155.
2. Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., "Numerical Recipes in Fortran", 2nd ed., Cambridge University Press, New York, 1992.
3. NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 10 https://www.nist.gov/srd/refprop
4. Cullimore, B., Ring, S., Johnson, D., "Auxiliary Sample Problem: Stratified Cryogenic Tank", C&R Technologies, 2015.