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Thermal Modeling of CryoFILL liquefaction tests

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Abstract. Proposed NASA missions to Moon and Mars involve producing cryogenic propellant in-situ to reduce launch mass and requirements. One technique for liquefaction of the gases produced through electrochemical processes is to circulate cold gaseous neon or helium through broad area cooling tubes attached to the outside of the propellant tanks. To determine the performance of this liquefaction process tests were conducted at NASA Glenn Research Center in a 2.1 cubic meter tank with a broad area cooling network (CryoFILL). A thermal/fluid model of the tank and its cooling loop is developed in Thermal Desktop. Details of the model and the model predictions and comparison to some of the experimental data from the CryoFILL liquefaction tests are presented here.

1. Introduction

Current NASA human mission architectures include In-Situ Resource Utilization (ISRU) on the surface of Moon and Mars to decrease launch mass, reduce launch requirements, and simplify the descent vehicle design. An ISRU plant can significantly reduce the landed mass [1]. The gaseous oxygen (GOX) and methane that the ISRU plant produces need to be liquefied and stored as propellants for ascent vehicles.

Heat radiated and conducted to the propellant tanks cause cryogenics to pressurize and boil off. In the absence of effective thermal protection and control measures, the storage tanks will rise in pressure. Thus, a portion of the vaporized liquid must be released to preserve the structural integrity of the tanks. To extend the lifetime of the liquefied propellants, an energy efficient refrigeration and storage system will also be required.

NASA has been developing technology to allow for the production and storage of propellants on the surface of both Mars and the Moon. A method of liquefaction being considered is the Broad Area Cooling (BAC). In broad area cooling, gaseous helium or neon is circulated through tubes attached with good thermal contact to the outside surface of the propellant tank. The BAC gas is cooled by a cryocooler prior to removing heat from the tank and thereby liquefying the gas flowing into the tank.

Application of zero boil-off (ZBO) technology to prevent vaporization will ensure propellant storage for extended periods of time. ZBO development work has been ongoing at NASA with a focus on employing the BAC approach. This concept and its associated technologies were demonstrated in a series of tests performed at the NASA Glenn Research Center (GRC) [2].

Operations for liquefaction of pertinent gases inside of lander propellant tanks have not been fully demonstrated. In addition to the demonstration of steady state operations, it is important to understand



and be able to model the performance of the hardware in transient operations. This may allow an integrated system to be operated over wider ranges of environmental and off-nominal power conditions. The Cryogenic Fluid In-situ Liquefaction for Landers (CryoFILL) project was established to fill this gap. In preparation for oxygen testing, nitrogen testing was performed on similar hardware to validate the liquefaction concepts [3-5].

2. CryoFILL System

CryoFILL is an effort undertaken by NASA to develop and demonstrate a flight-representative liquefaction system using broad area cooling [6]. A part of this effort is to develop predictive performance models that can be used to design and analyze propellant liquefaction and storage systems. The modeling approach is to demonstrate that test performance is consistent with predictive models.

The CryoFILL test hardware consists of an Aluminum 5052 tank that is 2 m tall by 1.25 m in inner diameter, holding a volume of 2.1 m³, Figure 1. The tank is installed within the NASA GRC's Small Multipurpose Research Facility (SMiRF) thermal vacuum chamber. It is covered with an MLI blanket consisting of 40 layers of aluminized Mylar and is suspended from the vacuum chamber lid. A nitrogen cooled thermal shroud encompasses the tank.



Figure 1. CryoFILL tank & BAC tubes (left). Cryocooler cold head enclosure (right).

An integrated cryocooler system provides cooling to a neon loop which is routed over the tank through a “tube-on-tank” heat exchanger that consists of eight 12 mm inner diameter tubes. Manifolds at the top and bottom of the tank ensure even distribution of the flow into the tubes. An Absolut cryofan is employed to flow neon from the top of the tank to the bottom of the tank to minimize stratification inside the tank. The neon gas cools the walls of the test tank and allows for condensation of the gas inside of the tank. Gaseous oxygen is fed into the tank using a flow controller.

The cryocooler system is composed of three CryoMech AL300 cryocoolers. Its cold heads, heat exchanger (HX), and the cryofan are enclosed in an evacuated enclosure, also shown in Figure 1. Only one cold head was active in the tests conducted providing up to 200 W of cooling at 90 K to the neon loop.

Instrumentations in the test system include temperature, pressure, fill level, and flow sensors. Silicon diodes are employed to measure fluid temperature down the middle of the tank. Temperature sensors monitor temperatures of the tank wall, the neon flow loop, the thermal shroud, and other test hardware.

Tank and neon loop absolute pressure sensors along with differential pressure sensors across the cryofan and the HX provide system pressures. Oxygen flow rate measurements on the inlet and outlet (vent line) of the system allow for accounting of the fill level and comparison to the capacitance probe used inside the tank. Neon loop flow rate is assessed both directly through a Coriolis flow meter as well as indirectly using temperature sensors across the cryocooler HX and the differential pressure across the cryofan. Heaters on the tank and the neon loop provide additional test variables.

3. Modeling Approach

An analytical model of the CryoFILL test setup is developed in Thermal Desktop, Figure 2. Thermal Desktop is an industry standard software used to build CAD-based thermal models. Its FloCAD module allows the ability to build fluid flow models, such as piping and tanks, and model fluid heat transfer. The integrated model includes the liquefaction tank, the BAC tube network, the cryocooler/heat exchanger and the cryofan. Radiation from the environment to the wall surfaces is calculated by the RadCAD component of Thermal Desktop.

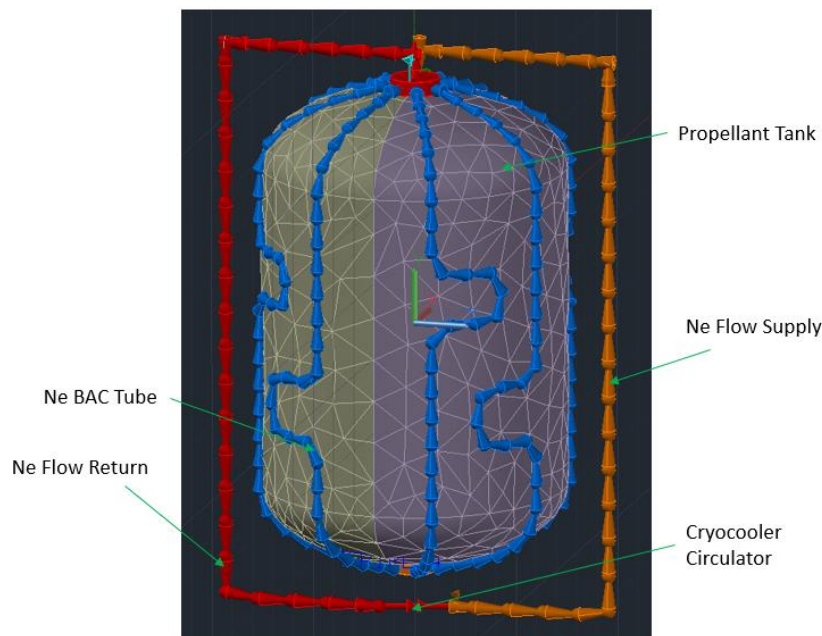


Figure 2. Thermal Desktop model of CryoFILL including the BAC lines and the cryocooler/cryofan.

Modeling the dynamics inside a cryogenic tank is a complex problem because of the different heat and mass transfers taking place. There is heat transfer between the environment and the tank wall as well as the heat transfer from the tank wall to the gas and the liquid inside the tank. Heat and mass transfer take place at the liquid-gas interface. There is also heat and mass transfer between the fluid in the tank and the gas entering the tank. Lastly, heat transfer between the tank wall and the cooling flow lines must be included in the CryoFILL model.

The tank in the model has many wall nodes. Only one node defines the entire liquid volume and another node defines the entire vapor volume, i.e., no stratification is modeled inside the tank. Heat transfer between the wall and the fluid inside is modeled with FloCAD pool boiling ties which perform pool boiling and condensation calculations. The BAC tubing network is added on the tank with FloCAD pipe flow components.

The neon flowing through the BAC tubes absorbs both internal and external heat loads on the tank wall. Thermal contact conductance between the tubes and the tank is not experimentally determined and is a model variable. During the tests the cryofan is nominally operated at 20 kRPM delivering a neon

flow rate of approximately 8.4 g/s. This is obtained from dividing the cold head cooling capacity based on the cold head temperature by the enthalpy change across the cold head heat exchanger.

The cryocooler/HX components are not explicitly included in the model as they are not the focus of this study. Rather, they are modeled such that the neon temperature immediately downstream of the HX matches that in each test case considered.

4. Model vs. Experimental Results

Nearly forty tests were performed during the CryoFILL liquefaction test series. The Thermal Desktop model developed has facilitated analysis of all the tests several of which are discussed here. To assess the viability of the model its predictions are compared to the test results presented below.

The test matrix started with a boil-off test, Test 1, to characterize parasitic radiative heat load from the shroud and conductive heat loads from the supports, the vent and fill lines imposed on the tank. During this test the tank was half filled with liquid oxygen (LOX), the neon loop was stagnant and the tank vent was open as oxygen boiled off due to heat leak from the environment. The boil off rate was measured by two flowmeters. The model predicted parasitic heat loads into the tank during the boil-off test are 39 W including 18 W of radiative heat load from the 250 K shroud.

An autogenous pressurization test, Test 1a, followed the boil-off test to allow separation between condensation on the liquid-vapor interface and that on the tank wall without the cryocooler operating. Gaseous oxygen near 300 K was introduced into the ullage at a rate of 1.24 kg/hr (0.34 g/s) with the tank nearly 50% full. The tank pressure variation during Test 1a is shown in Figure 3. After stopping the gas flow the pressure in the tank slightly decreased.

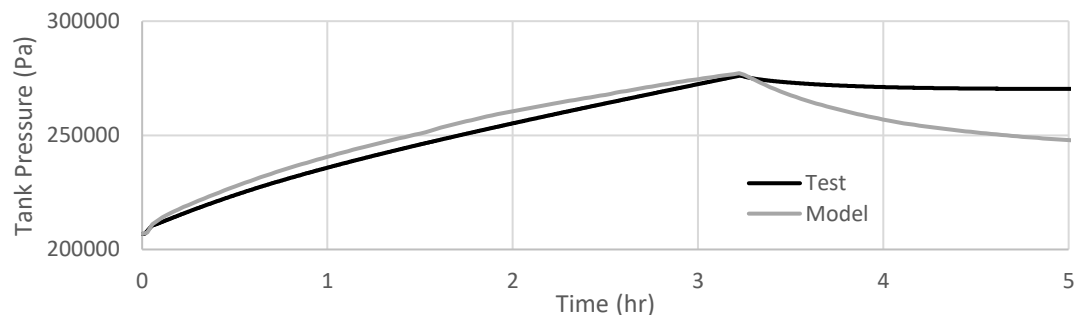


Figure 3. Test 1a – Tank pressure.

Test 2 was a zero boil-off (ZBO) test at a 58% fill volume. The neon mass flow rate was 8.4 g/s. The tank pressure was controlled to 207 kPa (30 psia) by employing the oxygen flow controller. ZBO was achieved when the heat applied to the tank is raised to 90 W while maintaining that applied to the neon loop at 64 W, Figure 4.

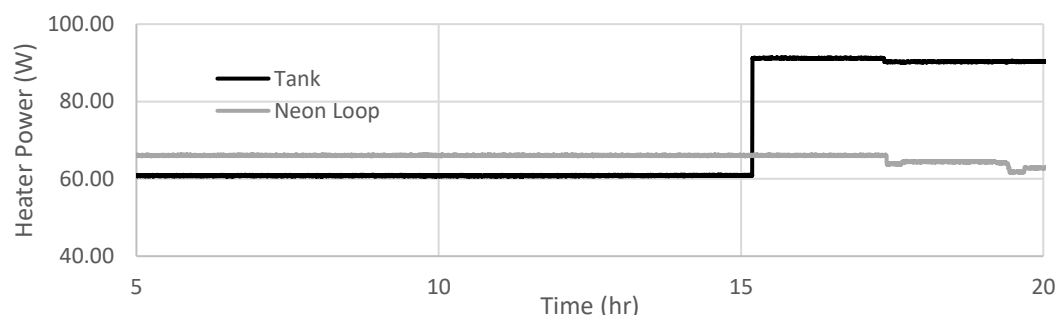


Figure 4. Test 2 – Tank and neon loop heater powers.

The tank pressure is shown in Figure 5 while the mass flow rate associated with Test 2 is in Figure 6. Oscillations in model pressure and flow rate have a lower frequency than those observed in the test.

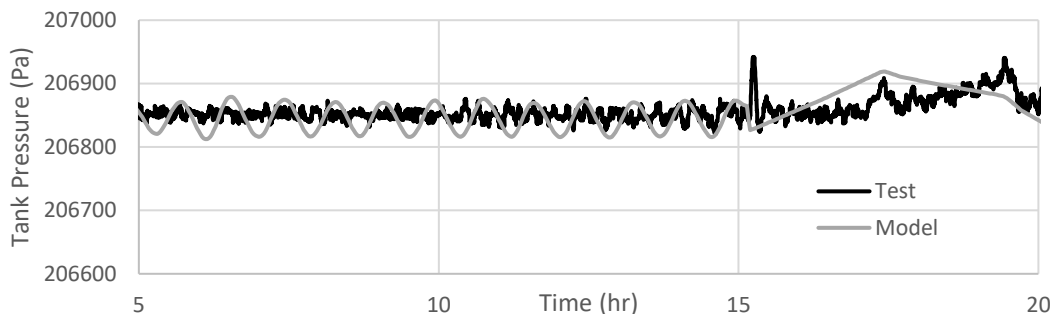


Figure 5. Test 2 – Tank pressure.

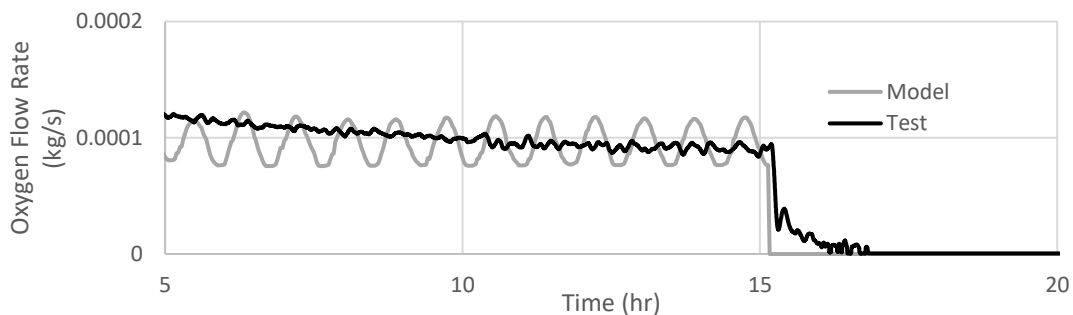


Figure 6. Test 2 – Gaseous oxygen flow rate.

The first oxygen liquefaction demonstration was conducted in Test 3 where the tank was initially 58% full. The gaseous oxygen flow rate into the tank ullage was 0.27 kg/hr at the start and increased to 1.1 kg/hr after 17 hours in conjunction with reduction in tank and neon loop heater powers. The neon flow rate was 8.3 g/s for the duration of the test. Figure 7 shows the heat loads on the tank and on the neon loop to maintain a constant tank pressure of 207 kPa during oxygen liquefaction.

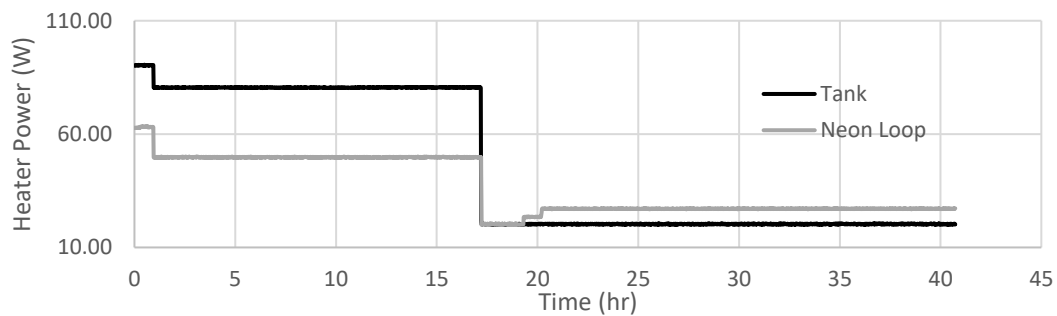


Figure 7. Test 3 – Tank and neon loop heater powers.

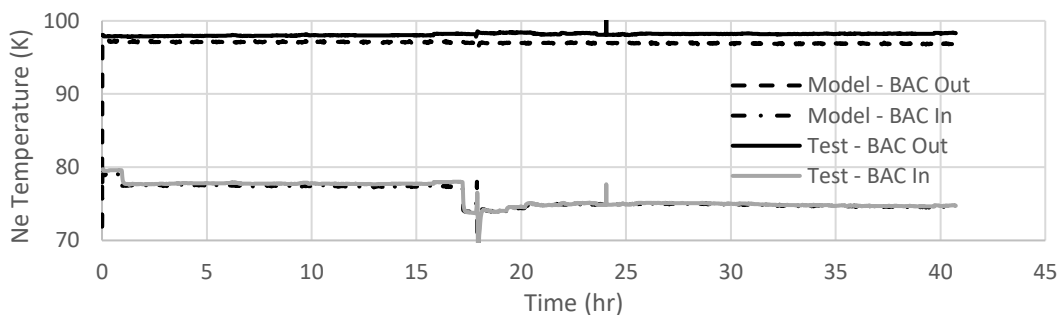


Figure 8. Test 3 – BAC neon inlet and outlet temperatures.

Figures 8-11 compare model results against the Test 3 data. The neon temperature in the BAC inlet and outlet manifolds are shown in Figure 8. Gaseous oxygen flow rate, tank pressure and liquid oxygen volume are presented in the subsequent figures.

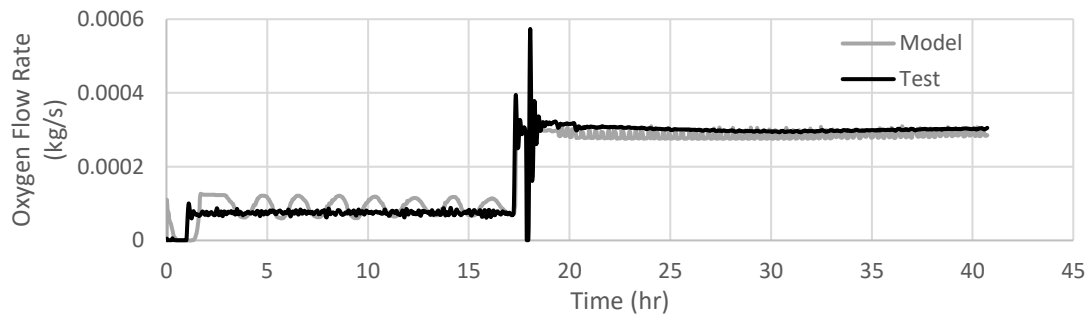


Figure 9. Test 3 – Gaseous oxygen flow rate.

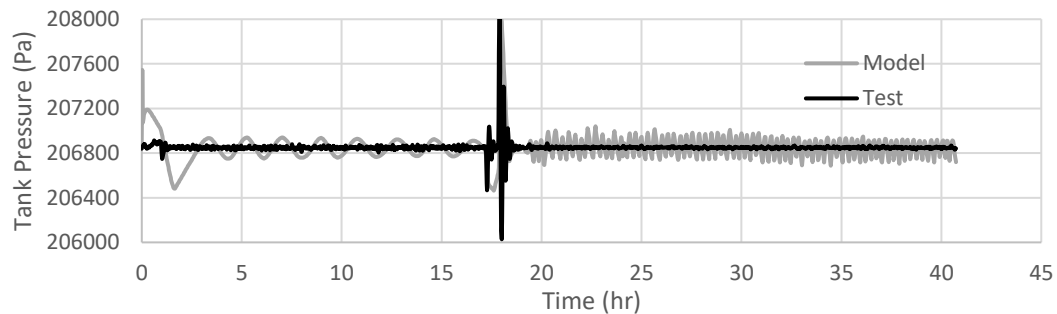


Figure 10. Test 3 – Tank pressure.

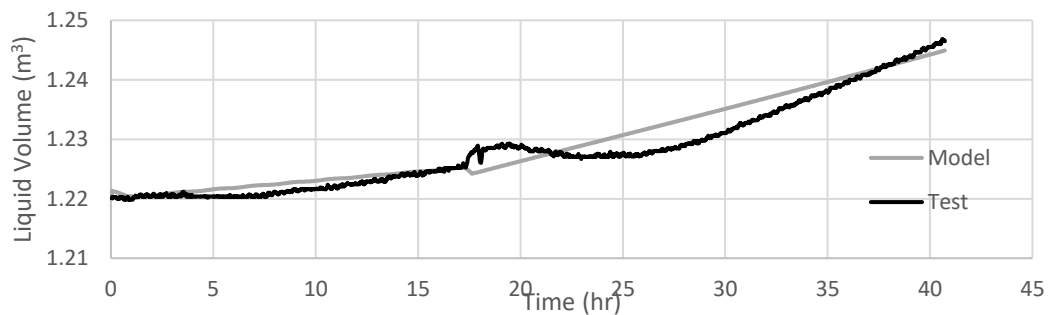


Figure 11. Test 3 – Liquid oxygen volume.

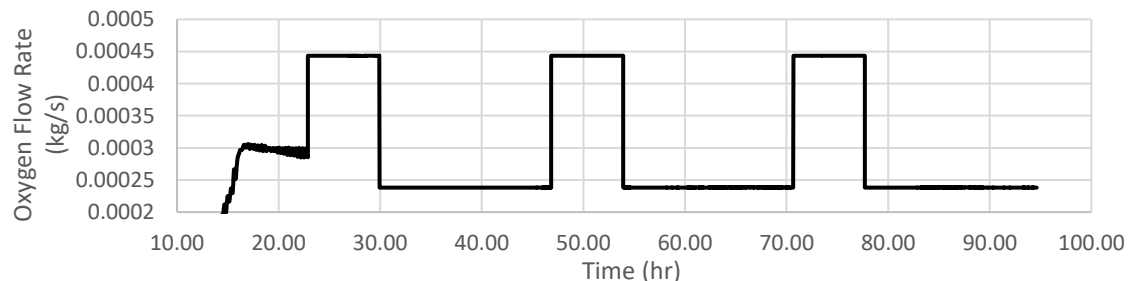


Figure 12. Test 27 – Gaseous oxygen flow rate.

In the transient liquefaction portion of the test matrix the oxygen flow rate, the environmental temperature, and the cryocooler effective heat removal rate (neon heater power) were independently varied while the pressure response was observed. In Test 27 the incoming gaseous oxygen flow rate was varied as seen in Figure 12. The neon flow rate was 7.4 g/s. The tank pressure response for this test is

shown in Figure 13. In Test 27 the tank internal temperatures show a degree of stratification during the higher gaseous oxygen flow rate parts of the test [6] which the present model does not reproduce.

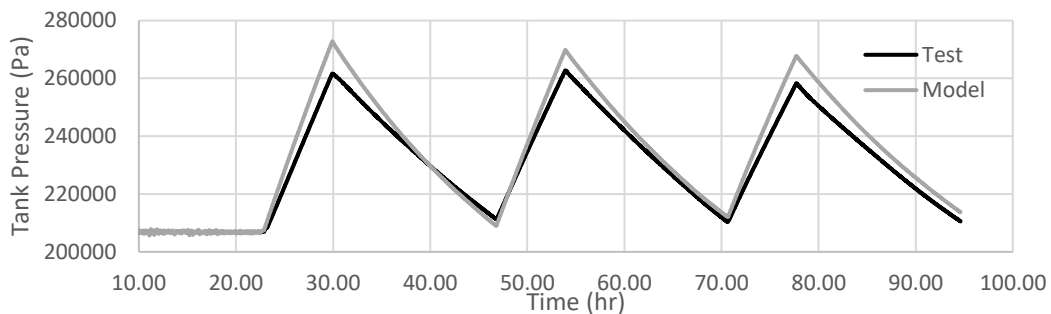


Figure 13. Test 27 – Tank pressure.

In Test 29-2 the tank was initially 4% full. The tank and neon loop heaters were varied as shown in Figure 14. The gaseous oxygen was injected into the ullage at a rate of 1.1 kg/hr. The neon flow rate was set to 7.2 g/s and was lowered to 5.8 g/s from hour 13 to hour 30 at which time the tank was vented to 207 kPa. The tank pressure response from this test is shown in Figure 15.

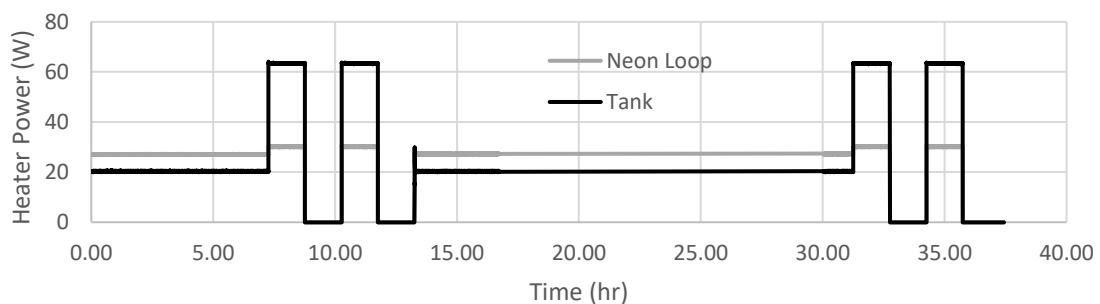


Figure 14. Test 29-2 – Tank and neon loop heater powers.

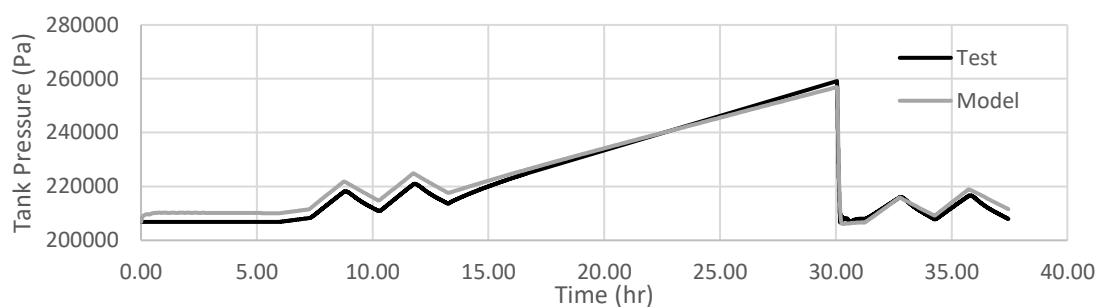


Figure 15. Test 29-2 – Tank pressure.

In Test 31 the tank was less than 2% filled with liquid oxygen. During this test the shroud temperature varied between 225 K and 290 K, Figure 16. The oxygen flow rate and the neon flow rate were 1.1 kg/hr and 7.2 g/s, respectively. The pressurization response for this transient case is complicated, Figure 17. The average pressure rate during the pressurization periods is 1.67 kPa/hr and that during the depressurization periods is -0.49 kPa/hr.

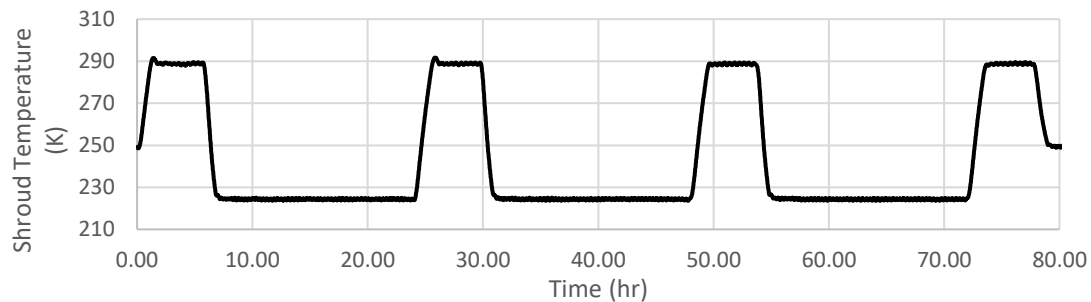


Figure 16. Test 31 – Shroud Temperature.

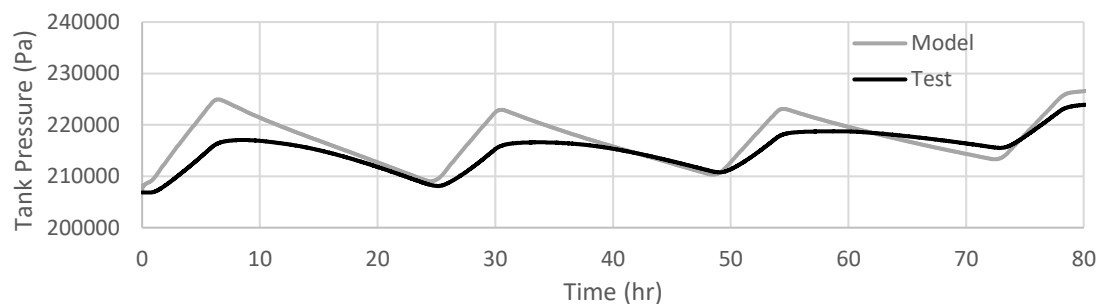


Figure 17. Test 31 – Tank Pressure.

5. Conclusions

The Thermal Desktop model of the CryoFILL liquefaction system predicts the experimental results reasonably well. To match the liquefaction model results to the experimental observations several model parameters had to be adjusted such as the neon flow rate, the tube to tank contact conductance, and the parasitic heat loads on the tank.

The thermal contact conductance between the BAC tubes and the tank was set to 0.1 W/cm-K. The neon flow rate calculated from the cryocooler HX temperature data was reduced by 5% to match the experimental results. In modeling the liquefaction tests the total parasitic heat load on the tank had to be increased over that observed in the boil-off test. The largest uncertainty in the test parameters appears to be in the parasitic heat loads. Furthermore, there is a higher degree of uncertainty in modeling the transient liquefaction tests.

To enhance the liquefaction modeling future work could include stratification in the Thermal Desktop model. Employing CFD modeling may also help better understand the fluid dynamics that occur in the liquefaction process.

A Final Report documenting the results of modeling all the CryoFILL tests is being developed.

6. References

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