Propellant liquefaction modelling compared against liquefaction testing

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Abstract. Current 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 are being conducted at NASA Marshall Space Flight Center in a 4.25 cubic meter tank with a broad area cooling network. A transient computational fluid dynamic code coupled with a thermal model of the tank and its cooling loops is developed in Thermal Desktop to compare against the results of these tests. Details of the model and the model predictions and comparison to experimental data from recent 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 and methane that the ISRU plant produces need to be liquefied and stored as propellants for ascent vehicles.

A method of liquefaction being considered is the Broad Area Cooling (BAC). In broad area cooling, gaseous helium or neon is circulated through tubes thermally attached 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.

Heat radiated and conducted to the propellant tanks cause cryogens 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.

Application of zero boil-off (ZBO) technology to prevent vaporization will ensure propellant storage for extended periods of time. Development work on this concept has been ongoing at NASA with a focus on employing the BAC approach. This concept and associated technology was demonstrated in a series of tests performed at the NASA Glenn Research Center (GRC) [2].
NASA is also employing broad area cooling as a liquefaction method to liquefy gaseous oxygen into cryogenic propellants. The broad area cooling acts as a heat exchanger to cool and condense the warm propellant entering the tank from the production plant. As part of this effort test an analytical approach has been taken to verify that the tank itself provides sufficient heat transfer area for liquefaction at the required rates.

2. BAC liquefaction system
An effort is undertaken by NASA to study liquefaction process using the BAC method. The purpose of this effort is to develop and demonstrate a flight-representative liquefaction system. A part of this effort is to develop predicative 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 predicative models.

NASA plans to demonstrate liquefaction of oxygen using the BAC technique. To this end, a BAC liquefaction system is being developed at NASA GRC. Prior to commissioning of this system a series of tests are being conducted with LN2 as a simulant cryogenic fluid because it is safer and easier to work with. LN2 and LO2 properties are sufficiently similar for the purposes of this effort.

These liquefaction tests are being conducted at NASA Marshal Space Flight Center (MSFC) [3] using a tank previously used for ZBO tests performed at NASA GRC with liquid nitrogen [2]. The test tank (figure 1) is stainless steel with a diameter of 1.2 m, and a wall thickness of 4.8 mm. The tank height is 1.4 m. The end caps have elliptical profiles and are axially separated by a 0.68-m cylindrical section.

The tank is supported by six struts via three attachment plates. At the top port of the tank (used for tank venting), a cooling strap is coupled as close to the tank as possible to reduce the vent-line temperature.

Two MLI blankets, each with 38 Mylar layers are used to minimize the radiation heat load on the tank. The Mylar is 6.4 microns thick and aluminized on both sides with two Dacron netting spacers placed between each Mylar layer.

The BAC system, that is the distributed cooling tubing network, consists of ten 304 stainless steel tubes—five supply and five return tubes—distributed evenly around the tank and then passing vertically down the tank wall. Each tube has an outside diameter of 0.635 cm and a wall thickness of 0.089 cm. The tubes are spaced at 36° intervals about the circumference of the tank and are coupled together at the tank top using two manifolds, 1.27 cm in diameter, as shown in figure 1. Cooling tubes are epoxied on the tank along the length of each tube.

Cooling of the Ne gas is accomplished by employing a Gifford-McMahon cryocooler. The cooler has a nominal cooling capacity of 150 W at 80 K. A heat exchanger developed by CryoZone fits on the cooler cold head to facilitate heat removal from the circulating fluid. To circulate the cooling gas through the BAC network a CryoZone (Noordenwind Cryofan) circulator is employed.

The liquefaction tank is placed inside a vacuum chamber (figure 2). The plumbing inside the chamber is covered by MLI. To reduce pressure oscillations in the BAC network a room–temperature buffer volume (0.049 m³) is connected to the BAC network by a ~5-m long, 0.51-cm diameter tube.

The liquefaction test setup is instrumented with a number of pressure and temperature sensors at various locations on the BAC network as well as on the tank. Flow rates of Ne through the BAC network and the nitrogen gas into the tank are monitored with several flow meters. However, a thermometer rake that was used to measure the fluid temperature inside the tank during the ZBO tests at NASA GRC was not included in the initial series of tests at MSFC. It is planned to include a tank thermometer rake in the upcoming tests at MSFC.

A total of eight tests were compared against the thermal model developed for this study. In these series of tests the nitrogen flows into the tank at the top. For the first five tests the nitrogen is injected into the tank at a constant rate of 0.126 g/s. For these tests the initial fill level of the tank is 0%, 25%, 50%, and 90% of the tank volume, respectively. In the next three tests the nitrogen flow rate is periodic, i.e., the flow is on for 12 hours at 0.252 g/s and off for 12 hours. This is to simulate environmental
temperature cycles on the planet surface. For the non-constant flow tests the initial fill level is 0%, 50%, and 90%. Each test was run for multiple days.

Figure 1. CAD model of the BAC liquefaction tank including the MLI blankets and the BAC tubes (left). Close-up of the BAC inlet and outlet manifolds (right).

Figure 2. BAC liquefaction test facility at NASA MSFC.
3. Modelling Approach

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

Modeling the dynamics inside a cryogenic tank is a complex problem because of the different heat and mass transfers taking place [4]. There is heat transfer between the environment and the portion of tank wall in contact with gas or that in contact with liquid. There is heat transfer from the tank wall to the gas and the liquid as well as heat transfer at the gas/liquid interface. There is mass transfer between the gas and the liquid and the gas entering the tank.

With the BAC network, there is also heat transfer between the tank wall and the tubing carrying the coolant, as well as, the coolant and the tubing wall.

The tank in Thermal Desktop (figure 3) has many wall nodes around the tank. No stratification is modeled inside the tank; one temperature defines the entire liquid volume and another temperature defines the entire vapor volume.

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 (figure 3). The coolant gas used in the model is neon.

The BAC tubes, the cryocooler/HX and the Cryofan are also included in the model. The coolant gas goes through a heat exchanger that is mounted on the cryocooler and cools before entering the BAC tubes. The tubing network is attached to the tank outside wall. The gas flowing through the BAC absorbs both internal and external heat loads on the tank wall. The thermal contact conductance between the tubes and the tank is not experimentally determined and is a parameter that is adjusted in the model. The circulator is modeled as a compressor; its pressure head vs. flow rate is provided by the manufacturer. The heat leak down the circulator shaft to the cold Ne gas is estimated to be 3 W which is removed by the cooler. During the tests the circulator is operated at 12000 RPM delivering a Ne flow rate of ~10 g/s at a pressure head 3.5 kPa.

The cryocooler is incorporated into the Thermal Desktop model as a variable temperature boundary node. 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 Ne temperature immediately downstream of the HX matches that in each test case considered.

Parasitic heat loads into the tank are approximately 10.5 W based on a boil-off test that was performed on the tank. These include the radiative heat loads as well the conductive heat loads from the support structure, the vent and fill lines. During the boil-off test there was no flow of Ne through the BAC flow tubes. The thermal model predicts approximately 4.7 W of radiative heat load on the tank, which is close to the values reported in reference [2]. Parasitic heat loads from the Cryofan and the Ne loop supports are also included in the model.

4. Modelling Results

All initial eight liquefaction tests performed at NASA MSFC were modeled as part of this work. Results from two of these tests, one constant and one non-constant nitrogen flow, are presented here. Figures 4-8 compare model results against test data for the constant nitrogen flow case with an initial fill volume of 25%. The first two figures show the Ne temperature in the BAC inlet and outlet manifolds. The next two figures present the tank pressure and the pressure in the Ne loop. The final figure represents the experimental liquefaction rate as well as the model prediction.
Figure 3. Thermal Desktop model of liquefaction system showing the BAC network, the circulator, and the cryocooler node. The pressure buffer volume in not shown.

Figure 4. Neon inlet temperature, constant nitrogen flow, 25% fill level.

Figure 5. Neon outlet temperature, constant nitrogen flow, 25% fill level.
To match the liquefaction model results to the experimental observations two model parameters needed to be adjusted. For all cases considered the thermal contact conductance (per unit length) between the BAC tubes and the tank wall is set at 0.15 times the temperature-dependent thermal conductivity of stainless steel. A second model parameter that is adjusted is the condensation layer thickness in the tank [5]. For low fill volume cases the model default value of 1 mm seems to adequately predict the pressure rise in the tank. However, for the 75% and the 90% fill levels this value has to be increased to better match the pressure rise in the tank. The thicker layer results in a higher heat transfer impedance between the nitrogen gas and the tank wall. As a result, the temperature difference between the ullage and the liquid is larger for these cases.

Except for the near empty tank case, for all other cases the tank wall temperature is fairly uniform. In the former case the tank wall temperature becomes uniform when the tank is above ~1% fill level.
Figures 9-13 compare liquefaction model results as well as the experimental results for the non-constant nitrogen flow case for the initial near empty tank. Figures 9 and 10 show the Ne temperature in the BAC inlet and outlet manifolds. The next two figures are the tank pressure and the pressure in the Ne loop. Finally, figure 13 compares the experimental liquefaction rate vs. the model prediction.

![Figure 9. Neon inlet temperature, non-constant nitrogen flow, empty.](image1)

![Figure 10. Neon outlet temperature, non-constant nitrogen flow, empty.](image2)

![Figure 11. Neon pressure, non-constant nitrogen flow, empty.](image3)
5. Conclusions
The liquefaction process utilizing a the tank wall as a heat exchanger has proven to work both experimentally and analytically using the Thermal Desktop system level thermal/fluid model. The Thermal Desktop model of the BAC liquefaction process predicts the experimental results reasonably well. However, the condensation layer thickness parameter in the tank needs to be increased for higher initial fill levels to predict the fluid pressure rise. Future MSFC tests plan to record the fluid temperature in the tank to improve the condensing fluid modelling. Additional models are being developed using a CFD tool to better understand the fluid dynamics and stratification that occurs when introducing warm gas inside the tank to improve condensation modelling predictions.

6. References
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