To be Presented at the 30th Space Cryogenics Workshop, Kailua-Kona, Hawaii, July 16-18, 2023

Modeling of a Large Scale Liquid Oxygen Propellant Transfer Test

Daniel Hauser, Bruce Wendt, Matthew Faykus

NASA Glenn Research Center

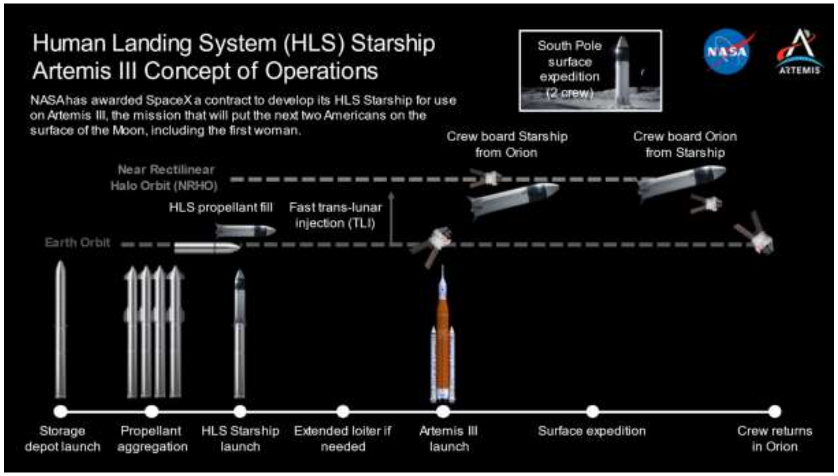
Lars Blackmore, Hiroumi Tani, George Thome

Space Exploration Technologies Corp

Cryogenic Propellant Transfer

- Current planned NASA missions to the Moon and Mars involve the on-orbit transfer of cryogenic propellants.
- Correctly predicting the flow rate during the propellant transfer process could help with planning these operations.
- In order to adequately predict the transfer of cryogenic propellant the two-phase thermodynamics and fluid dynamics needs to be adequately captured.
  - Cryogenic propellants are two-phase fluids that are more challenging to predict when compared to non-volatile fluids.
- The commercial thermo-fluid software Thermal Desktop was used to model the two-phase fluid and thermodynamics within the transfer system.
  - Thermal Desktop was used previously on RRM3 (Robotic Refueling Mission-3) to provide predictions on cryogenic methane propellant transfer.
    - Predicted flow rates within 10% of measured via RFMG and a turbine flow meter..

NASA HLS Starship Artemis III Concept of Operations



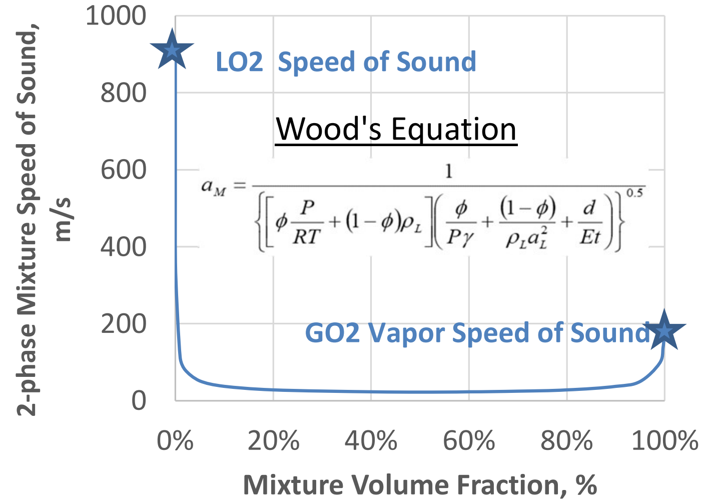
*Source: Watson-Morgan, U.B. (2022). "NASA's Initial Artemis Human Landing System" 73rd International Astronautical Congress(IAC) 18-22 September 2022, Paris, France,

- The Thermal Desktop model was anchored to two different sets of two-phase propellant transfer tests.
  - Lockheed Martin Propellant Transfer Test
    - Investigated the affect of propellant subcooling on cavitation and flow rate using liquid nitrogen.
  - SpaceX McGregor Ground Tests
    - Investigated the effect of upstream and downstream pressure and degree of subcooling on the propellant flow using liquid oxygen.

1) Liquid Methane Transfer Modeling for the RRM3 Experiment," D. Hauser, R, Boyle, A. Kashani, 2019 Space Cryogenics Workshop, Southbury, Connecticut

Challenges with Predicting Cryogenic Two-Phase Flow

- Cryogenic propellants are two-phase fluids, and the flow rate and pressure drop is more challenging to predict than non-volatile fluids.
  - These two phase propellant properties have similar characteristics to refrigerants.
- Cryogenic propellant transfer that occurs at or below the saturation pressure will result in two-phase flow.
  - The two-phase flow results in non-intuitive physics that need to be captured adequately as pressure drop is no longer a direct function of flow rate.
  - Choking occurs at different flow rates due to the differences in the speed of sound of the cavitating two-phase mixture.
- Unlike single phase flow where the quality and speed of sound are relatively constant, the pressure drop across the system is driven by the thermodynamics of the two-phase cryogenic mixture.
- To properly capture the two-phase thermodynamics and fluid dynamics correctly the entire fluid system needs to be modeled to accurately predict the flow throughout the system.



Predicting Cavitating Flow Across Valves and Orifices

- Unlike single phase flow where the flow rate across restrictions is a function of the pressure drop(ΔP), cavitating flow-rates are also a function of the fluid saturation pressure(P_{sat}), and ratio of the bubble growth time to liquid residence time ($\frac{\tau_b}{\tau_r}$).
- Thermal Desktop utilizes a correlation developed by J. Dyer for capturing the flow physics of propellants across flow orifices[1,2].
  - Calculates a single-phase flow rate(G_{spi}) and a homogenous equilibrium (G_{HEM} flow rate).
  - Uses the bubble growth ratio(κ) to estimate the maximum potential phase change across the orifice.
    - $\kappa = 0$, 100% potential phase change
    - $\kappa = 1$, 50% potential phase change
- Dyer's Model was validated against nitrous oxide two phase flow experimental data.
  - Correlation predicted the flow rate to be within 15% of the flow rate measured experimentally.
  - Compared to LO_2, Nitrous oxide has a higher NBP of 184 K but has similar thermal physical fluid properties.

Homogenous Equilibrium Flow Rate

$$G_{HEM} = \frac{\dot{m}}{A} = \rho_2\sqrt{2(h_1 - h_2)}$$

Single Phase Flow Rate

$$G_{spi} = \frac{\dot{m}}{A} = \sqrt{2\rho_1 \Delta P}$$

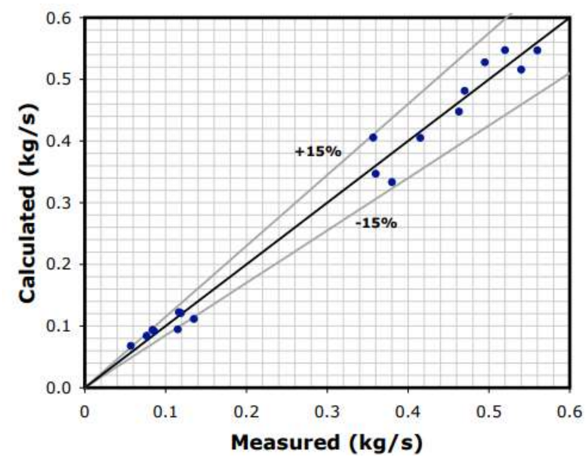
Dyer's 2-phase Flow Model

$$G = C_d\left(\frac{\kappa}{1+\kappa}G_{spi} + \frac{1}{1+\kappa}G_{HEM}\right)$$

Bubble Growth Time Ratio

$$\kappa = \frac{\tau_b}{\tau_r} = \sqrt{\frac{P_1 - P_2}{P_{sat} - P_1}}$$

Dyer's Model against Nitrous Oxide 2-phase Flow Experimental Data



1) "Modeling Feed System Flow Physics for Self-Pressurizing Propellants," J. Dyer et al, AIAA2007-5702.

2) Engineering Model to Calculate Mass Flow Rate of a Two-Phase Saturated Fluid Through an Injector Orifice." B. J. Solomon, Utah State University, report for Master's degree, Paper 110, 2011

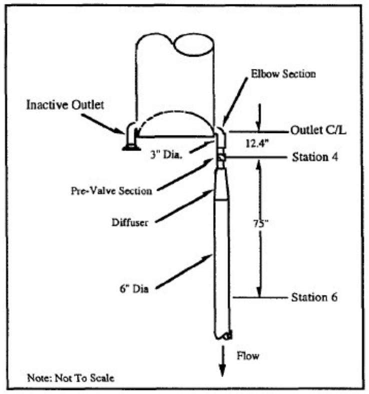
Lockheed Martin Atlas Downcomer LN2 Transfer Test

Previous LN2 Propellant Transfer Testing

- Cryogenic propellant transfer has been investigated previously by NASA and industry partners.
- Lockheed Martin performed a propellant transfer test for NASA in the 1990's to study the affect of subcooling and cavitation on the transfer flow rate[1,2].
- The ground test performed with LN2 consisted of a large 10,000-gallon tank, a sub-tank representing the Atlas LO2 tank, two feedline entrance elbows, a feedline with a flow valve at the end, and a catch tank.
- The test was heavily instrumented to determine the pressure and propellant temperature throughout various points of the transfer system.
  - For saturated flow conditions, the flow rate was calculated using the liquid column height within the propellant tank.
    - Authors reported a flow measurement accuracy of 5%, using subcooled fluid with a turbine flow meter.
- Various operating and design parameters were changed in the test including propellant subcooling level to investigate effect on cavitation and propellant flow rate.
- The tests showed that high flow rates could still be achieved with saturated flow.

Flow Test Facility

Cavitation Test Hardware



Experimental Flow Schematic

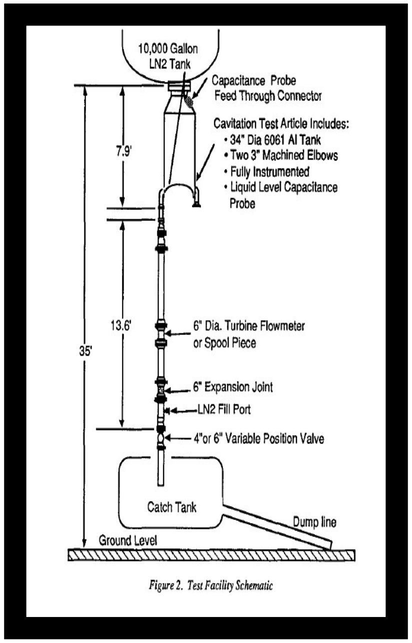


Figure 2. Test Facility Schematic

1) Mehta, Gopal, et al. "Cavitation Prediction and Prevention." *31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit July 10-12, 1995/San Diego, CA.*
2) Mehta, Gopal, et al. "Cavitation Prevention and Prediction (Part II)." *American Institute of Aeronautics and Astronautics, Inc. June 4th, 1996.*

LN2 Propellant Transfer Model Results Compared to Test Data

- A two-phase thermodynamic model of the LN2 downcomer test was created in Thermal Desktop to evaluate the model's capability at predicting two-phase flow including cavitation in engine or propellant transfer feed lines for tank to tank transfer.
  - The 10,000-gallon source tank was modeled as a FloCAD Compartment.
  - Cavitation Test Article modeled as 34" Diameter Pipe.
  - Only the "upper" elbow was modeled, located 7.3" from the bottom of the Atlas sub-tank. 3" hydraulic diameter, loss coefficient of 1.
  - Downstream control valve used to control the outlet resistance.
    - Loss factor at 100% Open, K=0.5 (Source: LM Report).
  - Downcomer was modeled as a 6" pipe. Wall roughness of 1.7E-4.
  - The Thermal Desktop model predictions were compared against the experimental flow rates measured for different levels of propellant subcooling: 0 °R (Saturated), 5 °R, 25 °R.

Experimental Flow Schematic

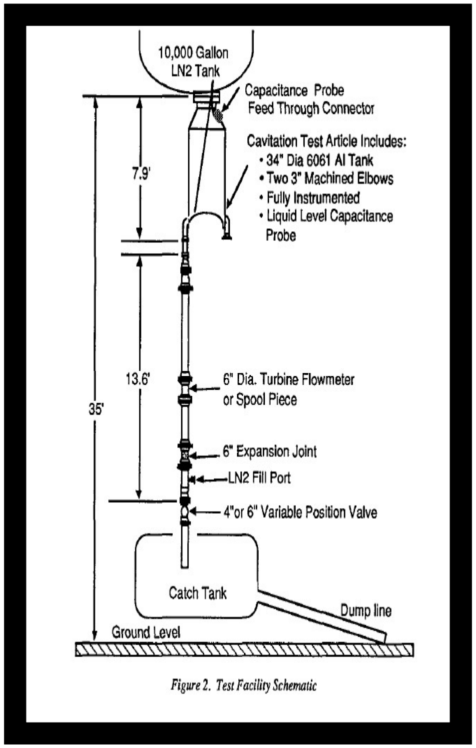
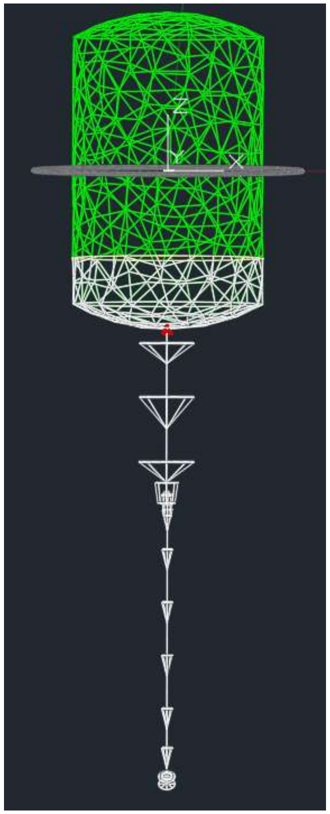


Figure 2. Test Facility Schematic

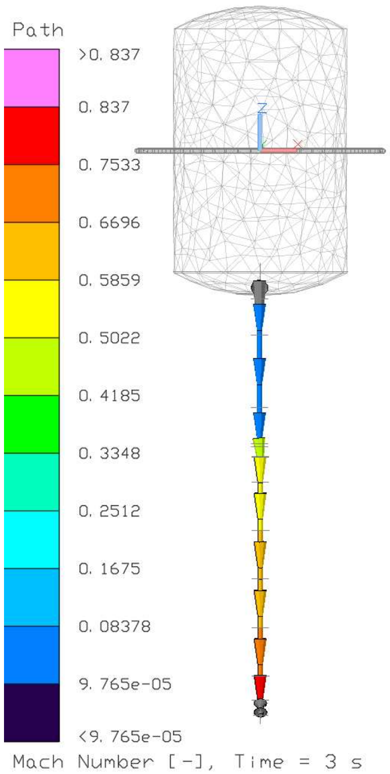
Thermal Desktop Model of LN2 Transfer Test



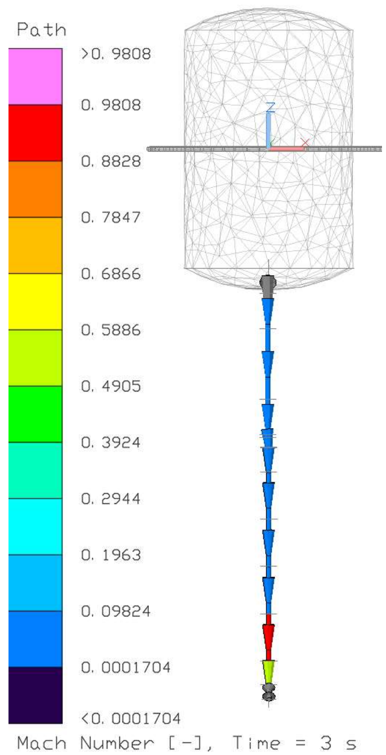
Saturated vs Subcooled(25 °R) Path Mach Number and Lump Void Fraction

Path Mach

Saturated

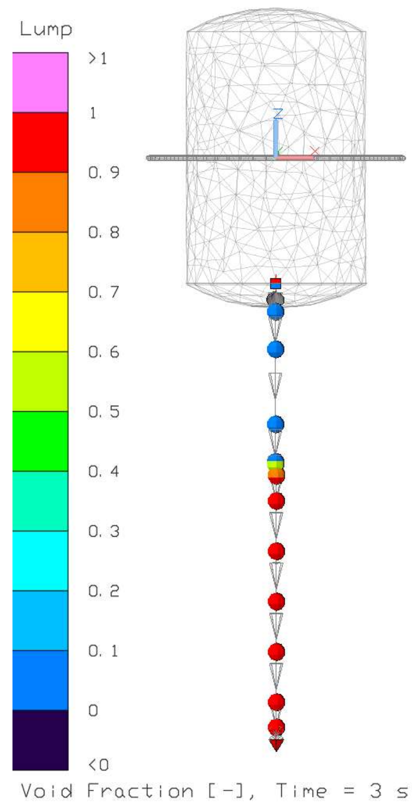


25 °R Subcooled

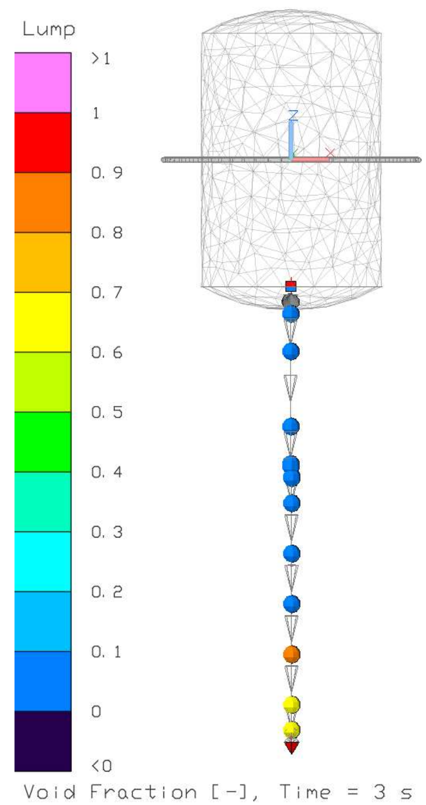


Lump Void Fraction

Saturated

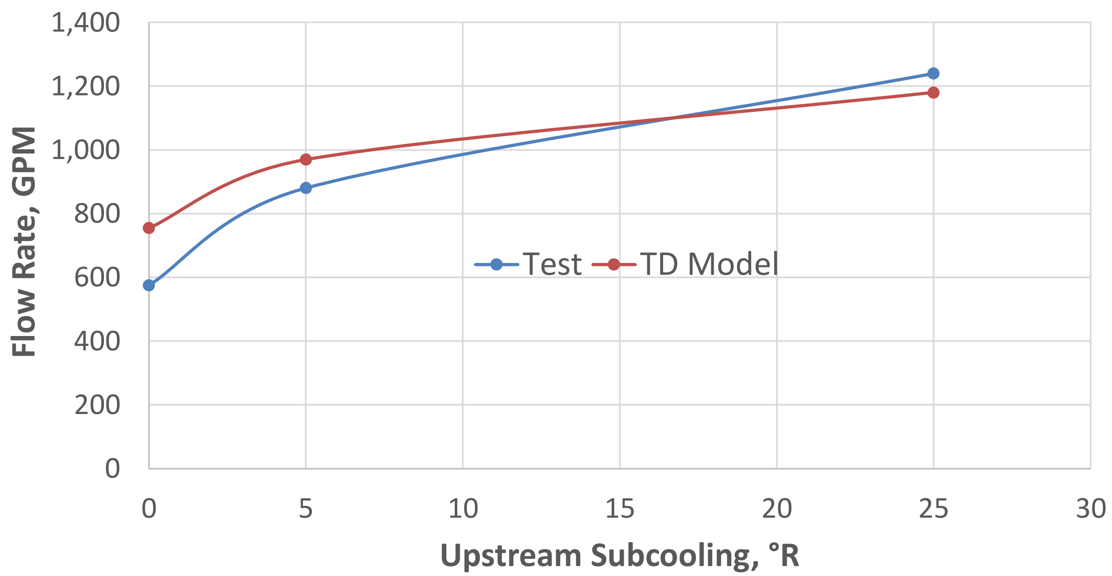


25 °R Subcooled



Saturated propellant results in flowing high void fraction two-phase flow. Resulting Mach number is larger.

LN2 Propellant Transfer Model Results Compared to Test Data (Downstream Valve Full Open)



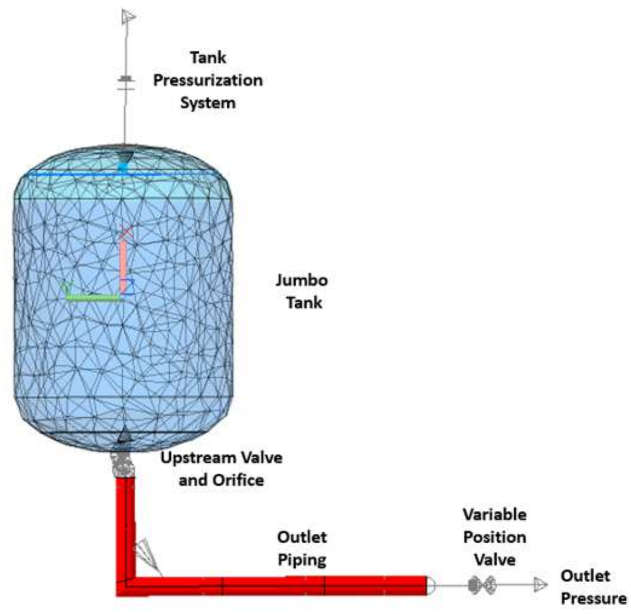
The Thermal Desktop model predicts the LN2 flow rates with a mean average error of 15% of the experimental measured flow rate

SpaceX Liquid Oxygen Propellant Transfer Ground Test

Liquid Oxygen Transfer Test

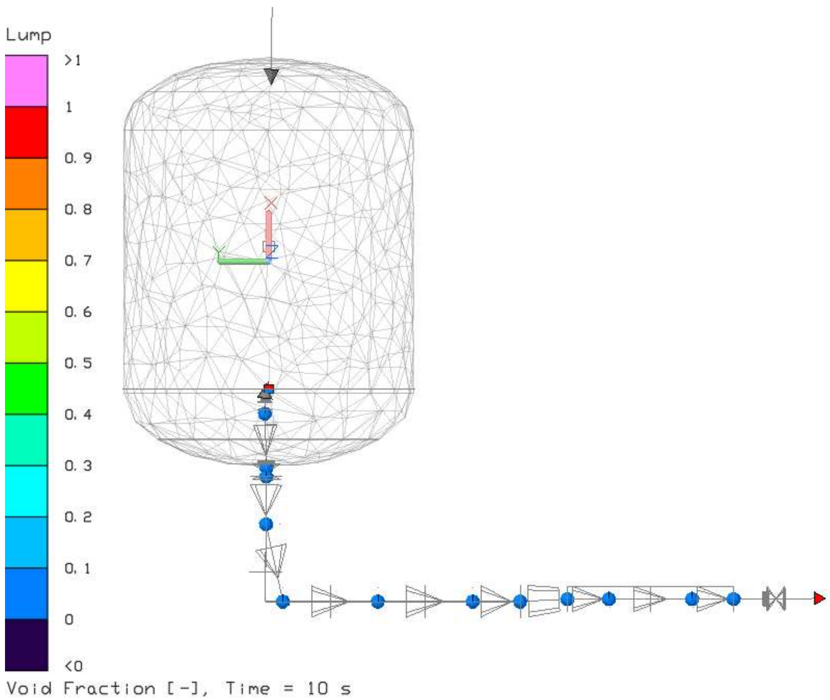
- A propellant transfer ground test was performed by SpaceX using liquid oxygen to further investigate the effect of varying the propellant thermodynamic conditions including:
  – Inlet/Outlet pressure
  – Inlet temperature and relative propellant subcooling
- The test was instrumented to measure:
  – Flow rate via liquid column height within the supply tank (Similar to Lockheed test)
  – Propellant Temperatures
  – Pressures (tank and downstream valve inlet)
- Pre-test, a Thermal Desktop two-phase flow model of the transfer system was created to provide pre-predictions of the flow rates based on the planned thermodynamic conditions for the test.
  – Helped confirm the planned test parameters.
- Post test, the Thermal Desktop model was run to predict the flow-rates using the measured as-run inlet/outlet thermodynamic conditions.
  – Component loss factors in the model were updated using experimental data from subcooled tests where two-phase flow or cavitation did not occur.
- The predicted flow rates were compared against the experimentally measured flow rates.

SpaceX Propellant Transfer Thermal Desktop Model

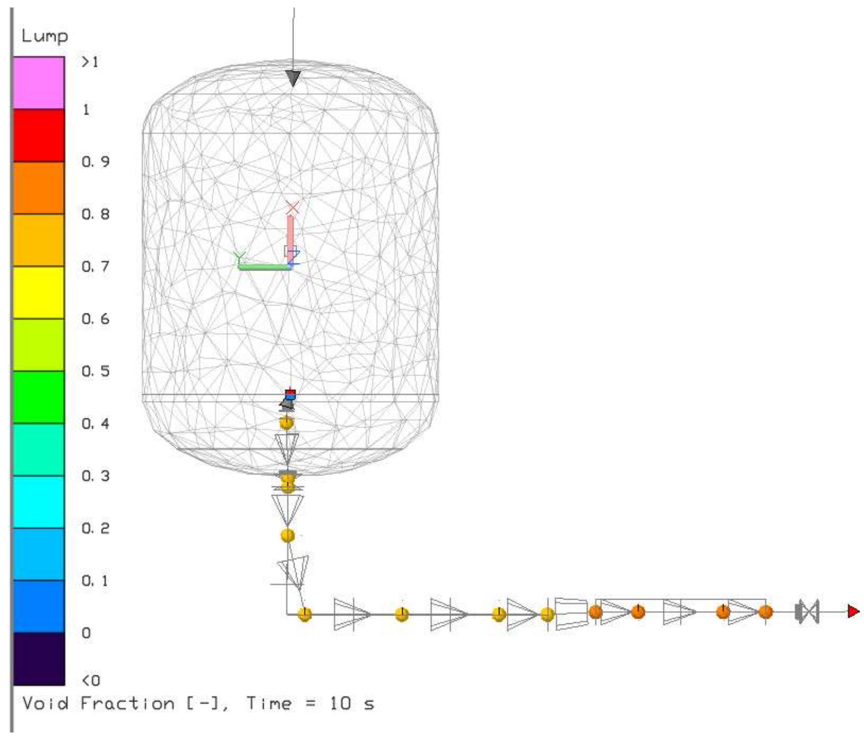


Transfer System Void Fraction for Subcooled and Saturated Flow

Subcooled Flow



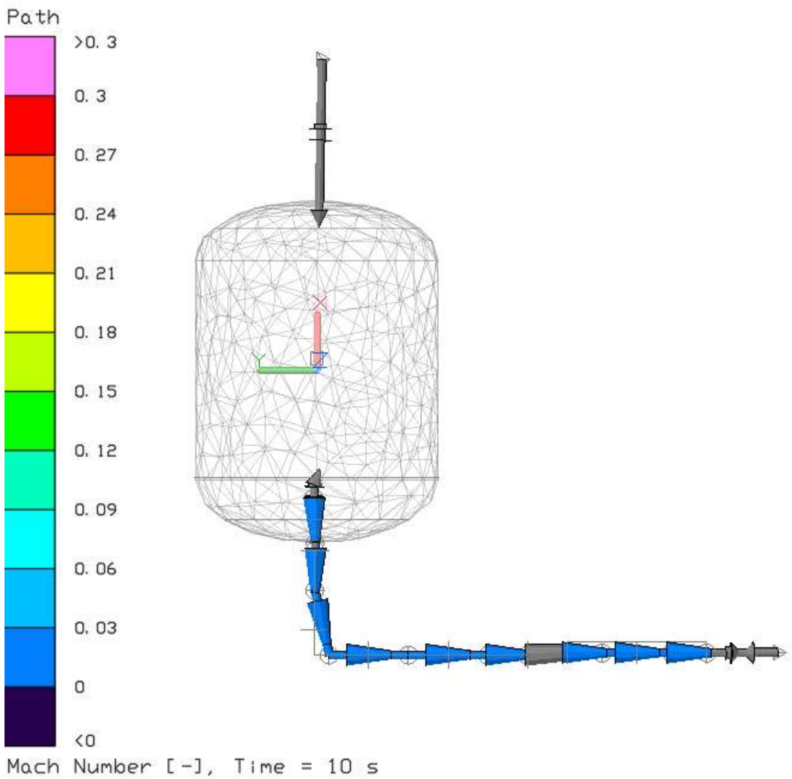
Saturated



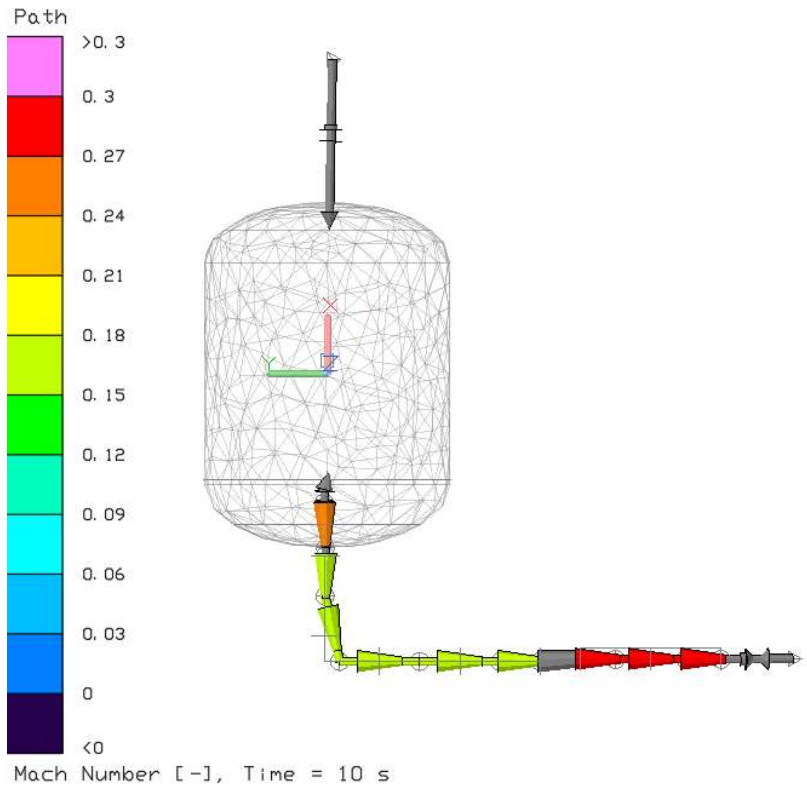
The model predicts 100% liquid throughout the transfer line for subcooled flow. Predictions for saturated liquid oxygen result are a mixture of mostly vapor by volume in the transfer line.

Transfer System Mach Number for Subcooled and Saturated Flow

Subcooled Flow

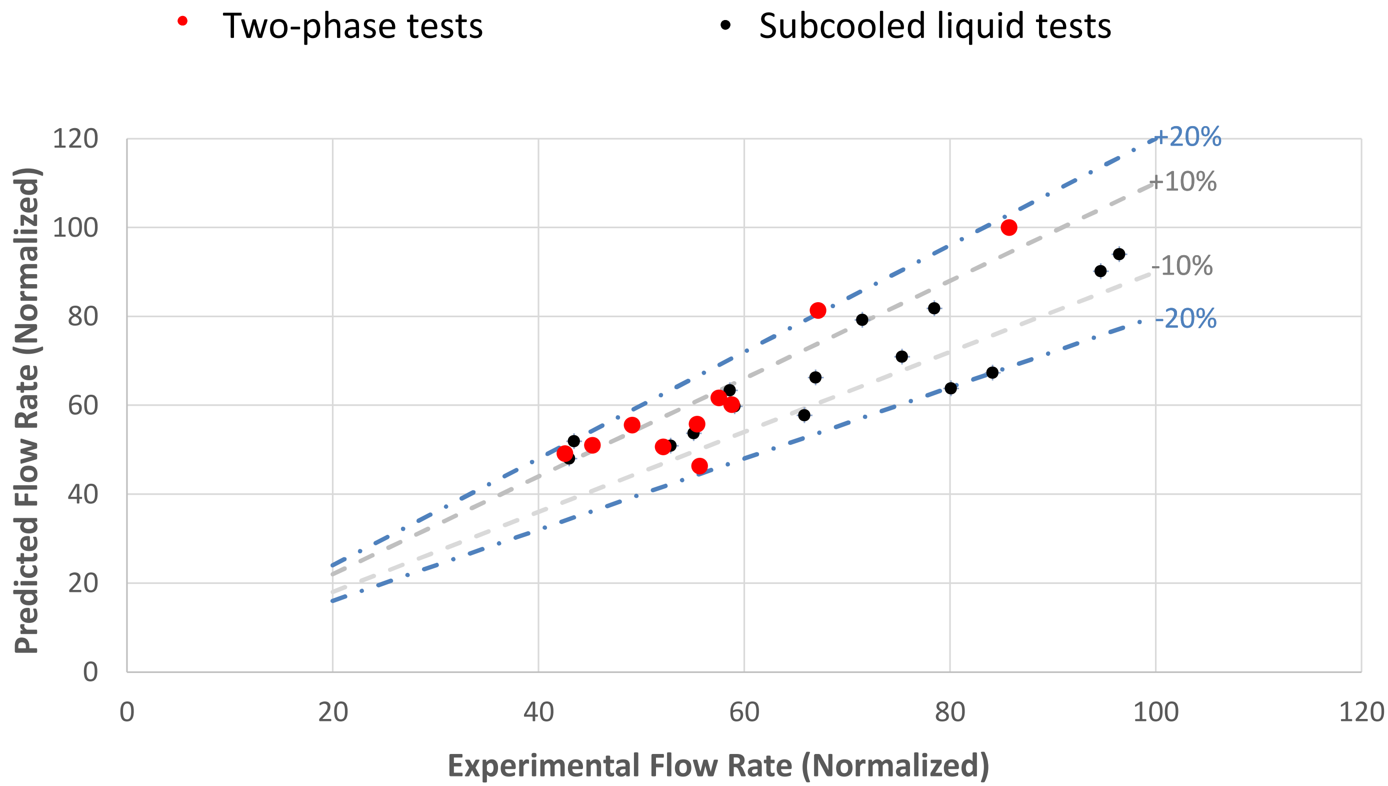


Saturated



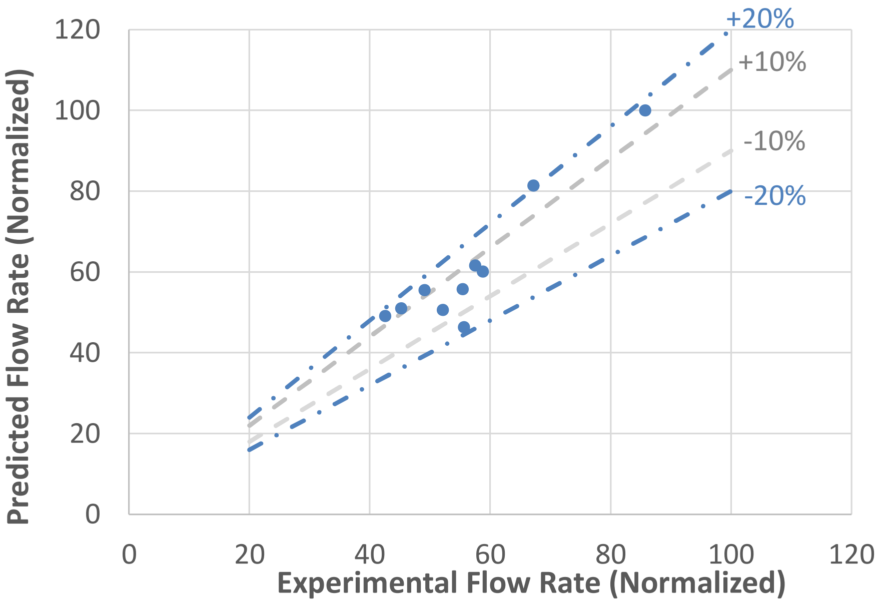
The model predicts low Mach numbers for subcooled liquid oxygen. For saturated flow the model predicts higher Mach numbers across the transfer system driven by the high void fraction two-phase flow.

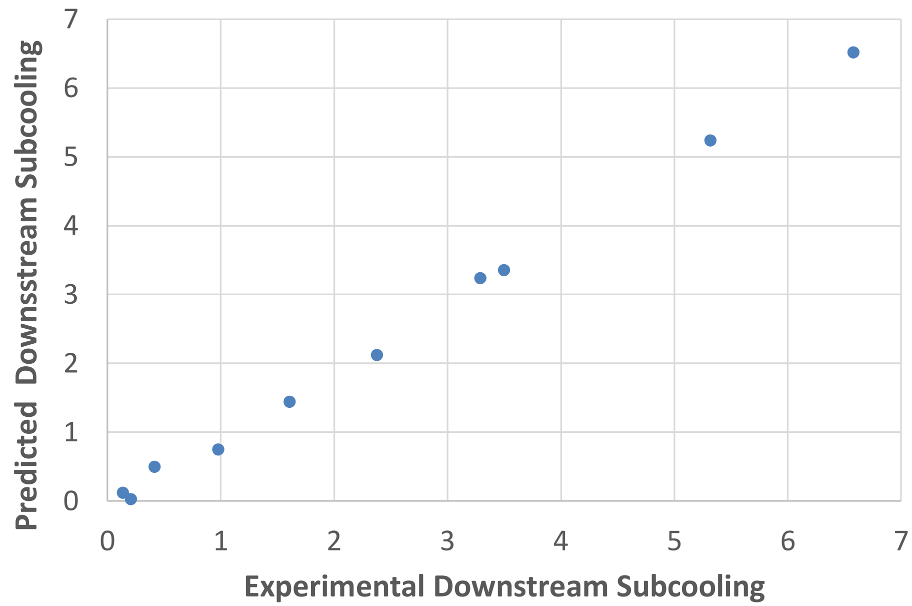
Experimental Flow Rates Vs Thermal Desktop System Model (All Cases)



For both single and two-phase flow cases, the Thermal Desktop model predicts the propellant transfer flow rate within a mean average error of 10% of the measured experimental flow rate.

Experimental Flow Rates Vs Thermal Desktop System Model (Cavitating 2-Phase Flow)





For cavitating two-phase flow, the model correctly predicted the flow rate within a mean average error of 9% of the measured experimental flow rate. The model also adequately captured the decrease in temperature across the transfer system due to the adiabatic expansion that occurs during two-phase flow.

Conclusions

- Predicting the flow of cryogenic propellants is non-intuitive due to the inherent two-phase nature of the volatile fluids.
- Capturing and modeling the two-phase thermodynamics and fluid dynamics across the entire transfer system can increase the ability to predict the performance of cryogenic transfer systems.
- Predictive Models were created of two different transfer systems using the commercial thermo-fluid software Thermal Desktop. The models captured the various fluid losses throughout the system including piping losses, valve/orifice losses, and hydrostatic pressure differences due to elevation changes.
  - The model used the Dyer two-phase flow correlation to estimate the two-phase flow rate across restrictions such as valves and orifices.
- The models were run using the as-tested conditions including inlet pressure, outlet pressure, propellant subcooling level.
  - For the Lockheed downcomer tests run with liquid nitrogen, the models on average predict the flow rates within a mean average error of 15% of the experimental measured flow rates.
  - For the SpaceX ground tests conducted with liquid oxygen, the model predicts the flow rates on average within a mean average error of 10% of the experimental measured flow rate across the slew of thermodynamic conditions.
- The results show that if the transfer system is adequately modeled to capture the two-phase flow thermodynamic and fluid dynamics across the entire system, the performance can be predicted with an accuracy on the same order of magnitude as single-phase flow.

Backup Slides

Nitrous Oxide vs Oxygen Thermal Physical Properties (1 Bar)

		Nitrous Oxide	Oxygen(O_2)
NBP	K	184.7	90.2
Liquid Density	kg/m3	1,230	1,141
Vapor Density	kg/m3	3.0	4.5
Density Ratio		414	255
Heat of Vaporization	KJ/kg	374	213
Liquid Cp	KJ/kg-K	1.7	1.7
Vapor Cp/Cv		1.4	1.4
Liquid Cp/Cv		1.8	1.8
Liquid Speed of Sound	m/s	1,134	904
Vapor Speed of Sound	m/s	213	177