

Modeling and Simulation of Tank Pressure Control using Zero-Boil Off Active Thermal Control for LOXSAT Technology Demonstration Mission

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I. Extended Abstract

To-date, research and modeling of cryogenic fluid management technologies (CFM) for spaceflight has been limited to ground tests, short-duration zero-g simulations (e.g. drop towers), and small-scale experiments on-orbit. There has not been a large-scale flight demonstration of a flight-like system. As future NASA missions to take humans further from Earth will require large, in-space cryogenic propulsion vehicles, it is imperative to begin collecting flight data for these systems to accurately model and design future vehicles. To meet this goal, NASA awarded tipping point technology demonstration awards to Eta Space, Lockheed Martin, Space Exploration Technologies (SpaceX), and United Launch Alliance (ULA) to demonstrate on-orbit storage and transfer of cryogenic propellant.

For its award, Eta Space is developing LOXSAT-1. It is a small satellite that will be launched on a Rocket Lab Electron rocket. The spacecraft consists of a Rocket Lab Photon spacecraft bus with a primary payload of a spherical liquid oxygen (LOX) storage tank with thermodynamic control systems. The primary objective of the mission is to demonstrate zero-boil-off storage of liquid oxygen. To accomplish this objective, the payload is equipped with an active thermal control system fluid loop that consists of propellant management device (PMD), positive-displacement pump, heat exchanger connected to a cryocooler, and a spray bar mixing injector.

When the fluid loop is operating, fluid is drawn from the tank by the PMD and pumped through the heat exchanger, lowering the fluid temperature below the fluid temperature in the tank. This subcooled liquid is then injected back into the tank through the spray bar. The subcooled injected liquid has two effects. If it is sprayed into the ullage space, the injected liquid will form into jets or droplets and exchange heat with the ullage gas. This will cool and condense the gas, reducing the pressure in the tank. Additionally, the liquid that is not sprayed through the ullage, as well as any remaining liquid spray from the ullage, will rejoin the liquid mass of the tank, lowering the bulk temperature of the liquid. These combined effects provide for zero-boil off pressure control by lowering the tank pressure and the liquid saturation pressure simultaneously, ensuring the liquid stays subcooled.

To model these complex mechanics and predict the performance of the active thermal control system, NASA is providing Eta Space with 3 parallel models of the tank. The approach of providing 3 different models allows for cross-checking and comparisons between the three to better understand how different modeling assumptions and selection semi-empirical factors affects the modeling result. Additionally, developing 3 models provides three different schemes for numerical simulation, providing confidence that results depict real physical phenomenon and not numerical quirks of the program.

Within the tank thermodynamics, there are two primary areas of heat transfer we concern ourselves with: the heat transfer between the ullage space and the droplet spray, and between the ullage space and bulk liquid. For the droplet heat transfer, there are multiple sets of assumptions that can be made and correlations that can be used. Currently, two working models - the TankSIM model and Easy5 model – provide for an overview of the different

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approaches available. The TankSIM model and Easy5 model use two different models for droplet heating and evaporation that illustrate how the models use different types of mechanisms to arrive at the same answer.

For the TankSIM model, droplets are treated as spheres of constant radius. Heat is transferred from the ullage to the droplet and warms the droplet until it reaches saturation, then the droplet begins evaporating and reducing its radius and mass. To calculate the heat transfer coefficient between the droplet and ullage, the Ranz-Marshall correlation is used. To determine the number of droplets in the ullage, a resident mass approach is used. This approach averages the number of droplets such that residuals at the start-up and shut-off of the spray bar cancel out. This same approach is used in the Easy5 model. The GFSSP model implements a linked list to track individual droplet “nodes” within the model.

For the Easy5 model, the droplet is assumed to have an interface at a temperature equal to the saturation temperature corresponding to the pressure of the gas phase. The heat transfer from the gas to the interface and the interface to the droplet bulk is then calculated, and the net mass transfer between the droplet and interface is determined by performing an energy balance across the interface. For the gas side of the interface, the Ranz-Marshall correlation is used. For the liquid side of the interface, a variety of correlations were tried, including Kronig and Brink (1950) and effective conductivity models.

As a result of these assumptions, the Easy5 model currently predicts faster depressurization, as at saturated vapor conditions, the heat transfer coefficient on the liquid side for the Easy5 model is greater than the heat transfer coefficient predicted by Ranz-Marshall used in the TankSIM code. This greater heat flux translates into faster condensation of the saturated ullage gas.

At the bulk liquid to ullage interface, the models are in much closer agreement. Both models model the ullage as a sphere centered within the bulk liquid in the tank, and both use the energy-jumping boundary condition to model heat and mass transfer across the interface. There are slight differences in how the interface temperature is calculated, however. The Easy5 model assumes the temperature of the interface is equal to the saturation temperature associated with the pressure of the gas phase. The TankSIM model calculates this temperature with Alabovskii’s equation, which provides a correction factor for interface temperatures.

Analysis tasks are focused on determining rates of depressurization within the tank during active cooling operation. To maintain net positive suction head at the pump inlet, the tank pressure cannot fall faster than the saturation pressure associated with the temperature of the bulk liquid. Additionally, there is interest in analyzing the performance of the loop at different pump speeds and cryocooler input powers. Adjusting the flowrate affects both the performance of the heat exchanger between the cryocooler and pumped liquid, and the heat transfer between the droplet spray and the ullage. Ideally, a pump speed and cryocooler power can be selected that will allow the tank to operate in zero-boil-off mode with a very narrow range of storage pressure.

Initial model results are shown below for the 3 models:

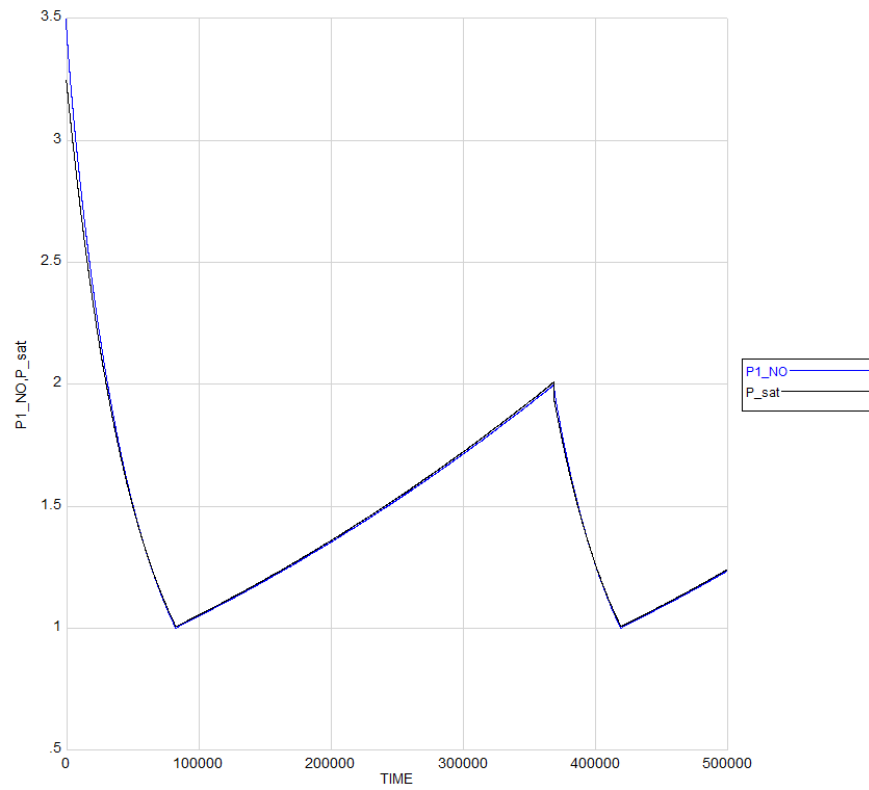


Fig 1. Tank Pressure and Liquid Saturation Pressure for one depressurization analysis case from the Easy5 model

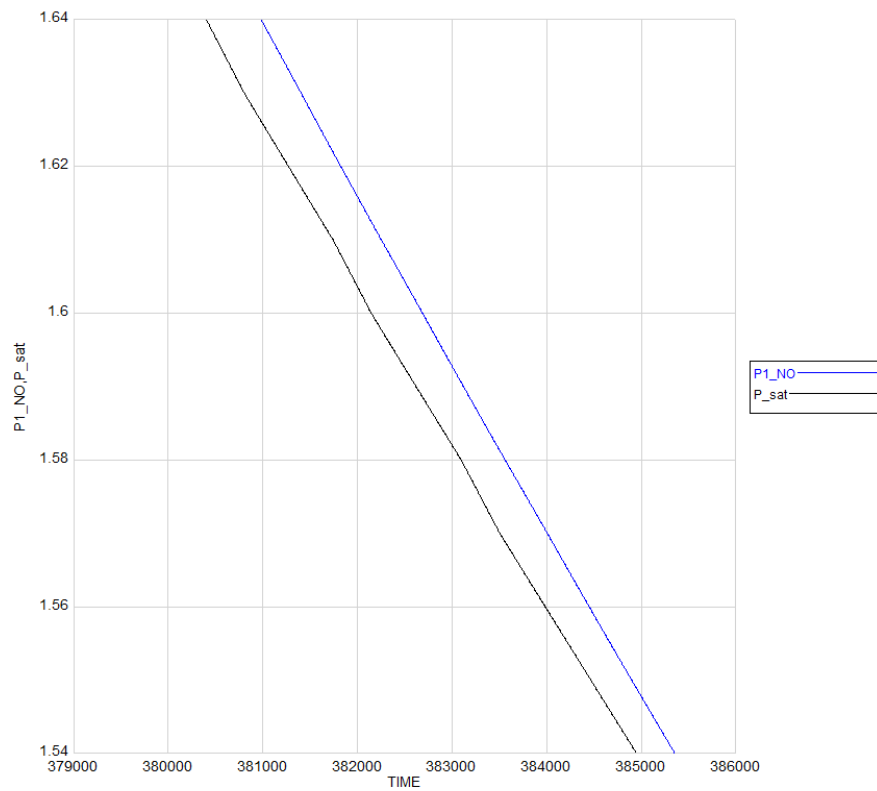


Fig 2. Tank Pressure and Liquid Saturation Pressure from the previous graph, enhanced during the second depressurization to show pressure delta

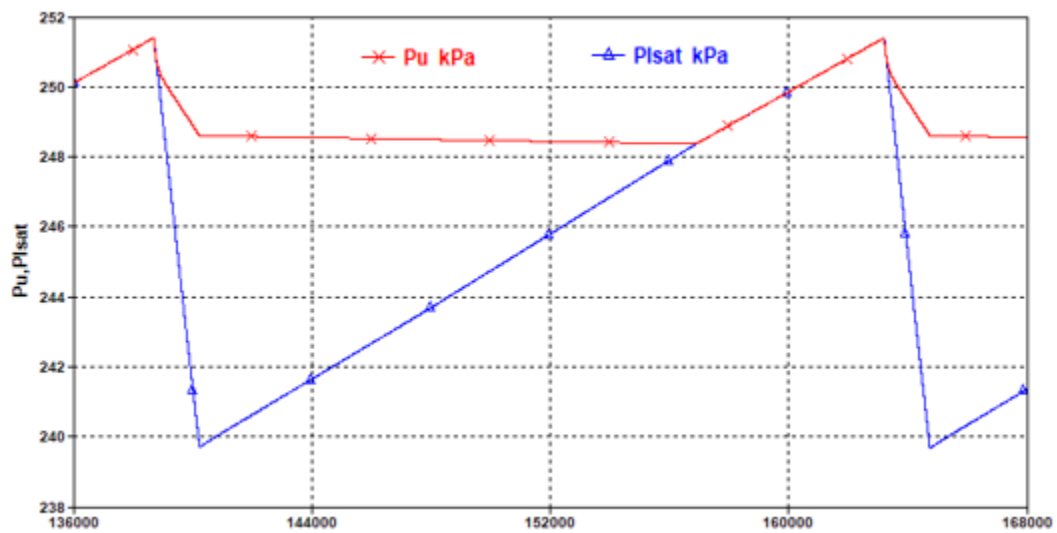


Fig 3. Tank Pressure and Liquid Saturation Pressure for one depressurization analysis case from the TankSIM model

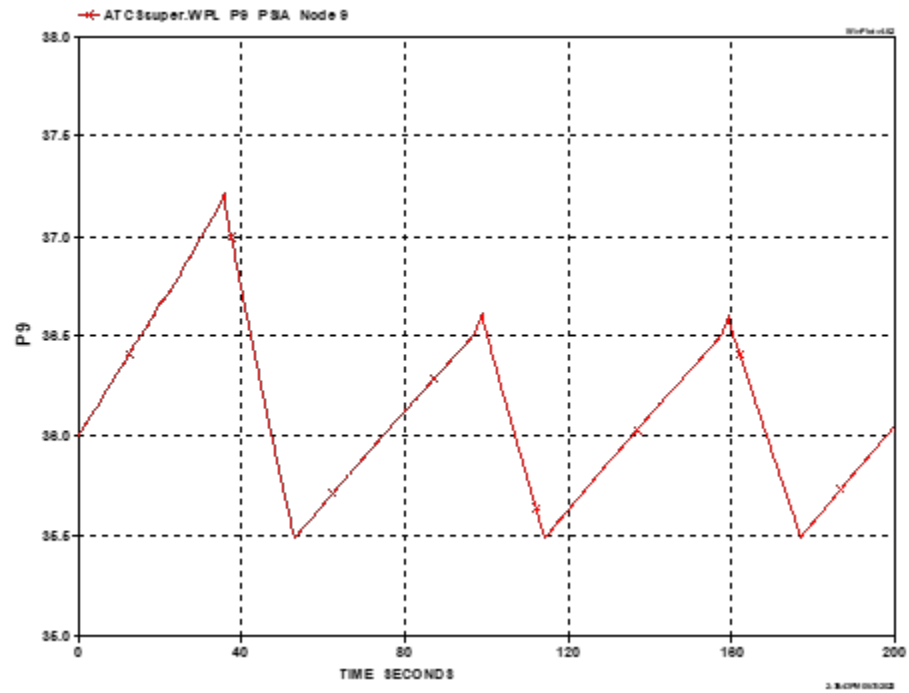


Fig 4. Tank Pressure for one analysis case from the GFSSP model