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Zero boil-off system testing

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ABSTRACT

Cryogenic propellants such as liquid hydrogen (LH_2) and liquid oxygen (LO_2) are a part of NASA's future space exploration plans due to their high specific impulse for rocket motors of upper stages. However, the low storage temperatures of LH_2 and LO_2 cause substantial boil-off losses for long duration missions. These losses can be eliminated by incorporating high performance cryocooler technology to intercept heat load to the propellant tanks and modulating the cryocooler temperature to control tank pressure. The technology being developed by NASA is the reverse turbo-Brayton cycle cryocooler and its integration to the propellant tank through a distributed cooling tubing network coupled to the tank wall. This configuration was recently tested at NASA Glenn Research Center in a vacuum chamber and cryoshroud that simulated the essential thermal aspects of low Earth orbit, its vacuum and temperature. This test series established that the active cooling system integrated with the propellant tank eliminated boil-off and robustly controlled tank pressure.

1. Introduction

To expand human presence into the solar system and onto the surface of Mars, NASA is considering high-specific-impulse propellant combinations, such as LH_2 and LO_2, for orbiting depots, orbit transfer stages, and for Mars surface. However, for volumetric considerations, cryogenic propellants are stored as liquids at extremely low temperatures. The heat radiated to the spacecraft from both the Sun and any other celestial body the spacecraft may be near (such as Earth, the moon and Mars) and heat conducted down to the storage tanks from other sources on the spacecraft cause LH_2 and LO_2 to pressurize and boil off (change state from liquid to gas). If this is left to its own devices, the storage tanks will overpressurize; thus they must vent some of the vaporized liquid, resulting in less propellant remaining available for propulsion. Because mission architecture loiter periods are projected to be months long [1], the vented vapor losses will be substantial. To allow for these losses during the long space missions envisioned, the stage would need to carry excess propellant which would be very heavy. Alternatively, NASA could use thick walled propellant tanks that operate at high pressure, but the additional mass of the heavier tanks would also be prohibitive. The application of Zero Boil-Off (ZBO) technology to prevent vaporization and keep storage tanks reasonably sized and low weight will enable missions to store adequate propellant quantities for long periods of time. Development work and testing on this concept using distributive cooling has been on going at NASA since 2007, with the cryogenic boil-off reduction system activities [2–4]. Analysis of this ZBO concept applied to liquid oxygen tanks predicts that it will reduce mass for missions in low Earth orbit (LEO) that have loiter periods greater than 1 week [5]. The preferred distributed cooling system utilizes the reverse turbo-Brayton cycle cryocooler and the circulator that is inherent to it. This concept and associate technology was demonstrated in a series of 10 tests performed at NASA Glenn Research Center's Small Multi-Purpose Research Facility (SMiRF). Three "passive," with the cryocooler system off, and seven that are "active," with the cryocooler system operational. The test series included tests performed at roughly 90% full and 25% full, and demonstrations of cryocooler excess cooling capacity countered with tests at reduced cryocooler capacity. The test series established that the prescribed cryocooler integration system eliminated boil-off and robustly controlled tank pressure.

2. Objectives

The purpose of the test was to demonstrate the performance of a flight representative liquid oxygen (LO_2) ZBO system. Given the lack of micro-gravity concerns with the active cooling system or on the unvented propellant, this demonstration, prepares the ZBO concept for flight with minor additional development required beyond scaling of components. To achieve this demonstration, three main objectives were identified.

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The first objective was to demonstrate robust zero boil-off storage of liquid oxygen. This requires a demonstration of the ability of the active cooling system to control and modulate tank pressure over an extended period of time. Besides achieving ZBO, a demonstration of the active cooling system dropping tank pressure is significant as it indicates the system has performance margin to account for various uncertainties in the design. Inherent in robust ZBO is the ability to model tank pressurization and depressurization. Because the distributed cooling system in the ZBO design promises to reduce thermal stratification, a simple homogenous model might be accurate. This is planned along with a comparison test, with the cryocooler off, to create a mapping of tank pressure versus net heat removed and added. The second objective was to determine the cryocooler's ability to eliminate boil-off at a low fill level. This is needed for propellant depot or upper stage mission concepts that have multiple transfers or propellant burns that need to be operational at fairly low tank fill levels. Low fill levels increase thermal gradients in the tank and the goal of this second objective is see if the ZBO system can minimize those increased thermal gradients and still maintain tank pressure control and ZBO. The third test objective was to validate the scaling model developed [5, p. 66] that predicts ZBO thermal elements, such as multi-layer insulation (MLI), the cryocooler, radiator, and solar arrays, reduce mass compared to always boiling passive only propellant storage, with MLI only, for loiter periods in LEO of just over one week. Given that this prediction is based on analysis, verification is required to ensure mission architecture consideration of the active cooling concept is done appropriately.

Although the mission architectures are interested in LO_2, the high testing costs associated with it caused us to use liquid nitrogen (LN_2) as a LO_2 simulant. A nominal pump fed propulsion system LO_2 storage pressure was assumed to be 173 kPa (25 psi), which corresponds to a saturated LO_2 temperature of 95.6 K. To accomplish this, the test tank was filled with LN_2 and pressurized to 565 kPa (82 psia). This is the saturation pressure when LN_2's saturation temperature (95.6 K) is equal to that of LO_2.

Fig. 1. LOX ZBO test article being lowered int the vacuum chamber.

3. Hardware description

3.1. Facility overview

The experiment was conducted at NASA GRC's Small Multi-Purpose Research Facility (SMiRF) [6]. SMiRF provided the two main aspects of a LEO simulation test—the vacuum of space and the temperatures of low Earth orbit (LEO). The SMiRF facility utilizes a cylindrical vacuum chamber with elliptical heads and achieved an average vacuum of 1×10^{-6} torr vacuum throughout the test series. To accurately simulate the space environment, an optically dense flat black painted thermal shroud, or cryoshroud, is fitted closely within the vacuum chamber walls. The cryoshroud is operated as a constant density closed loop GN_2 heating/cooling system which was operated at 220 K ±3 K for 9 of the 10 tests. The shroud reduces the maximum allowable size of the test article to a diameter 1.5 m and overall length of 2 m. The test article is shown in Fig. 1 attached to the vacuum chamber lid at SMiRF and being lowered into the chamber.

3.2. Liquid nitrogen test tank

The test tank is stainless steel with a diameter of 1.2 m and a 4.7 mm wall thickness that is 1.2 m^3 in volume. The tank height is 1.4 m and the length to diameter ratio is 1.15. The domes are 2:1 elliptical head domes with a 0.7 m long cylindrical section in between. The tank was attached to the six struts and via three attachment plates. The struts were 0.38 m long, having a tapered geometry with a maximum outer diameter of 19 mm and a 0.82 mm wall thickness. These titanium struts have spherical rod end bearings at both ends.

The tank has twelve heaters attached to its outer diameter at the bottom part of the tank cylinder, which allowed for rapid warm-up of the tank between tests.

The propellant tank maximum operating pressure was 620 kPa (90 psia). The nominal operating pressure was 565 kPa (82 psia).

At the top port of the tank, used for tank venting, a cooling strap was coupled as close to the tank as possible, to reduce the vent line temperature. This was designed and installed because of a pre-test finite element thermal model analysis that indicated a hot spot at the tank top. A model of the tank with the tank penetrations used and all the associated heat leak paths used in the thermal analysis is shown in Fig. 2.

3.3. Support ring

The support ring is suspended from the SMiRF chamber lid by three cables. The ring supports the tank, the cryocooler, and the radiator and is made from stainless steel. The layout of the components configured in the ring is shown in Fig. 3.

3.4. Radiator

The radiator was designed to remove 400 W of heat at 300 K. It is a curved aluminum panel that is 3 mm thick. Attached to this panel were four horizontal ammonia heat pipes of 9 mm diameter. At the end of the radiator panel is the evaporator plate where the cryocooler hot interface was attached. The radiator was insulated with 10 layers of MLI on its inside surface, to ensure that the vast majority of the heat radiates from its outer diameter surface. Its outer surface was painted white with Aeroglaze A276 paint with a measured emissivity was 0.935.