Pressure-Fed LOX/LCH4 Reaction Control System for Spacecraft: Transient Modeling and Thermal Vacuum Hotfire Test Results

Matthew J. Atwell[1], Eric A. Hurlbert [2], J.C. Melcher[3], and Robert L. Morehead[4]
NASA Johnson Space Center, Houston, TX, 77058, United States

Abstract

An integrated cryogenic liquid oxygen, liquid methane (LOX/LCH4) reaction control system (RCS) was tested at NASA Glenn Research Center's Plum Brook Station in the Spacecraft Propulsion Research Facility (B-2) under vacuum and thermal vacuum conditions. The RCS is a subsystem of the Integrated Cryogenic Propulsion Test Article (ICPTA), a pressure-fed LOX/LCH4 propulsion system composed of a single 2,800 lbf main engine, two 28 lbf RCS engines, and two 7 lbf RCS engines. Propellants are stored in four 48 inch diameter 5083 aluminum tanks that feed both the main engine and RCS engines in parallel. Helium stored cryogenically in a composite overwrapped pressure vessel (COPV) flows through a heat exchanger on the main engine before being used to pressurize the propellant tanks to a design operating pressure of 325 psi. The ICPTA is capable of simultaneous main engine and RCS operation.

The RCS engines utilize a coil-on-plug (COP) ignition system designed for operation in a vacuum environment, eliminating corona discharge issues associated with a high voltage lead. There are two RCS pods on the ICPTA, with two engines on each pod. One of these two engines is a heritage flight engine from Project Morpheus. Its sea level nozzle was removed and replaced by an 85:1 nozzle machined using Inconel 718, resulting in a maximum thrust of 28 lbf under altitude conditions. The other engine is a scaled down version of the 28 lbf engine, designed to match the core and overall mixture ratios as well as other injector characteristics. This engine can produce a maximum thrust of 7 lbf with an 85:1 nozzle that was additively manufactured using Inconel 718. Both engines are film-cooled and capable of limited duration gas-gas and gas-liquid operation, as well as steady-state liquid-liquid operation. Each pod contains one of each version, such that two engines of the same thrust level can be fired as a couple on opposite pods. The RCS feed system is composed of symmetrical 3/8 inch lines that tap off of the main propellant manifold to send LOX and LCH4 outboard to the RCS pods. A Thermodynamic Vent System (TVS) is used to condition propellants at each pod by venting through an orifice and then routing the cold expansion products back through tubing that is welded along a large portion of the main RCS feed lines.

Prior to final installation on the ICPTA, the RCS engines were tested in a small vacuum chamber at the Johnson Space Center (JSC) Energy Systems Test Area (ESTA) to verify functionality of the new COP ignition system and check out operation of the vacuum nozzles. After engine-level testing, the RCS engines were installed on the vehicle and a series of integrated hot-fire tests were performed at JSC consisting of various pulsing and steady-state firings as well as integrated main engine/RCS operation. The ICPTA was then integrated into the Plum Brook B-2 facility for vacuum and thermal/vacuum testing. Testing in the B-2 facility was composed of multiple thermal and pressure environments. The first set of tests were performed under ambient temperature and altitude pressure conditions. These tests consisted of a range of minimum impulse bit (MIB) pulsing sequences with low duty cycle, analogous to a coast phase in which the RCS is primarily used for station keeping. The primary goal of this sequence is to understand how propellant conditions were effected without an active TVS. In this scenario, consistent gas-gas operation is desirable since it results in a smaller MIB and more efficient propellant consumption. Multiple skin thermocouples are mounted on the feedlines, in addition to a submerged thermocouple on each commodity, in order to gather thermal data on the system. Higher duty cycle pulsing tests were then peformed, analogous to an ascent or

[1] Propulsion System Engineer, Propulsion Systems Branch EP4, AIAA Member
[2] Propulsion System Engineer, Propulsion Systems Branch EP4, AIAA Member
[2] Propulsion System Engineer, Propulsion Systems Branch EP4, AIAA Senior Member
[2] Propulsion System Engineer, Propulsion Systems Branch EP4, AIAA Member

landing mission phase. The primary goal of this sequence was to examine how well the engines self-conditioned without active TVS when starting from a quiescent state. The TVS was then activated during some tests to demonstrate the capability to quickly condition the engines for higher pulsing demand scenarios. A thermocouple at the TVS outlet allows for the calculation of energy absorbed by the vented propellant. Lastly, tests with longer pulses and multiple engines firing either in sequence or simultaneously were run in order to gather transient system response data on waterhammer. Six total high-speed pressure transducers are installed on the RCS system, one sensor at the end of each propellant manifold line on the pods, and one at the tap-off location for each commodity. This will allow for the accurate characterization of waterhammer in the system under various propellant conditions and firing sequences. Other instrumentation for this test series includes nozzle throat thermocouples, chamber pressure measurement, heat soakback measurement, and tank wall plume impingement temperature measurement. The next set of tests were performed to demonstrate simultaneous main engine and RCS operation. Data from this test will be used to examine if there is any change to nominal operation of the RCS as a result of feed system interaction or other phenomenon. Some of these tests began under high vacuum conditions (target ambient pressure less than $1x10^{-3}$ torr) and others began at altitude conditions. The last set of tests were performed with the B-2 cold wall active. Under these tests, many of the same low duty cycle MIB tests were repeated in order to characterize how propellant conditions changed with the lower heat leak. In this scenario the RCS manifold experiences much less heat leak, resulting in a change to how well the engines self-condition. As a result, an increase in maximum waterhammer pressures and a change in natural frequency of the system was expected due to higher density propellants. The lower heat leak should also result in a change to the MIB pulse profile, and data will be examined to understand how MIB repeatability is affected in the different operating environments.

Parallel to the test efforts, a set of transient model development efforts were made to predict RCS performance. The primary effort was aimed at producing a SINDA/FLUINT model to predict propellant conditioning up to the engine inlet as a function of different environmental and operating parameters, with the goal of predicting chamber pressure, TVS performance, and propellant consumption over time. Preliminary results for this effort will be presented in comparison with test data. Additional modeling efforts were made using SINDA/FLUINT to predict waterhammer in the system since the software is capable of handling multiphase transient fluid dynamics. These results will be compared with the high-speed pressure transducer test data for validation purposes.

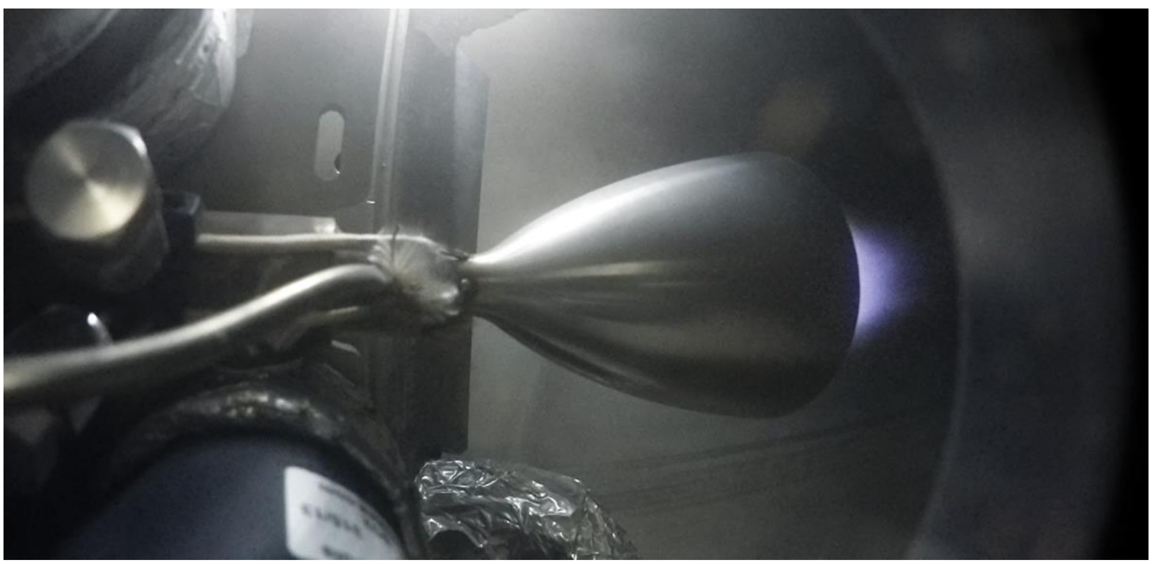

Figure 1. 28 lbf RCS engine ignition testing in a vacuum pipe prior to installation on ICPTA

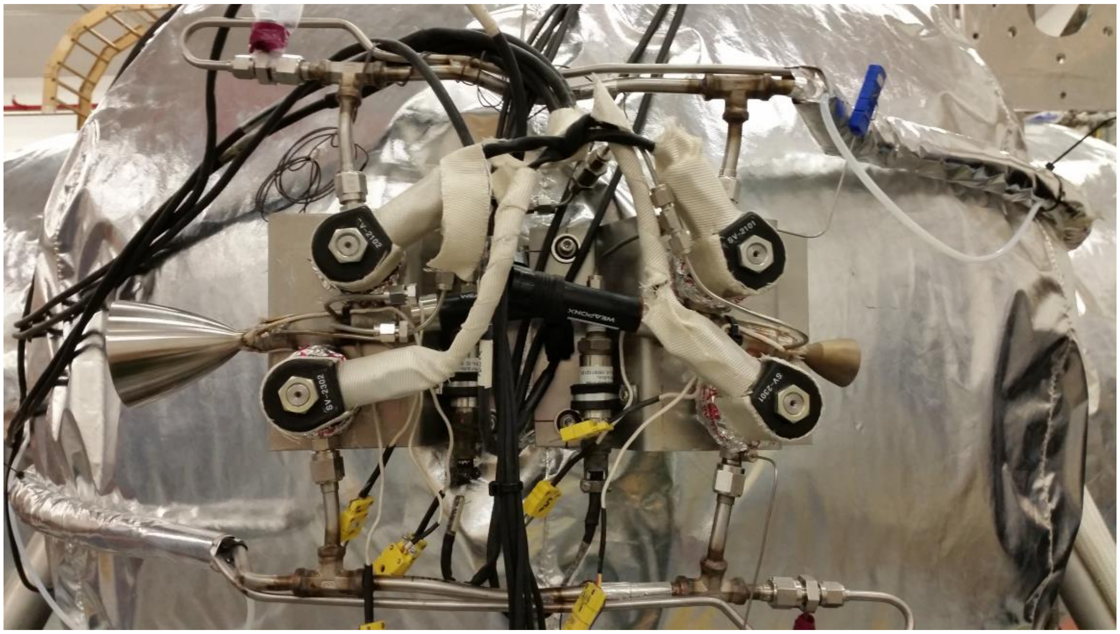

Figure 2. RCS pod with one 28 lbf engine (left) and one 7 lbf engine (right)