AN EXPERIMENTAL INVESTIGATION ON LOX/LCH4 REACTION CONTROL THRUSTERS

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Dedication

This work is dedicated to my parents, family, and friends who have supported me throughout my entire education.

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by

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THESIS

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Abstract

This work describes the development and preliminary testing of a thrust measurement system, in combination with a propellant feed and automation controls systems to test the performance of 8.9 to 35.6 N (2 to 8 lb_f) LOX/Methane reaction control thrusters. LOX/LCH_4 has come to be the main focus of next generation "green" propellants for future space exploration. As there is limited experience with this propellant combination, an effort is being conducted to research performance of rockets using these propellants. The development of a thrust measurement, propellant feed, and automation controls systems is necessary for proper testing and qualification of thruster performance. The propellant feed system includes three subsystems: (i) Liquid methane production and delivery subsystem, (ii) LOX delivery subsystem, and (iii) Propellants automated flow control and monitoring subsystem. A cart-based mobile liquid methane delivery system was designed in order to provide fuel to meet combustion requirements; a 2.2 L liquid methane production unit was also integrated within this system. Liquid methane production is accomplished with a condenser and utilizing liquid nitrogen as a chiller. Flow control and monitoring of the system is done remotely from a control room and is achieved by component commands sent through a LabVIEW program interface and a DAQ system. The program allows the automated execution of thruster experimental procedures and precision in control of timing and measurement. A torsional based thrust measurement system uses thrust to generate a moment upon a central axis, which induces displacement captured by a laser positioning sensor. Torsional pivots are used to provide a consistent and measureable resistance to thrust; displacement is correlated to a thrust value via the use of a calibration curve. Preliminary integration testing was conducted to ensure proper system functionality and response by firing a LOX/LCH_4 thruster at ambient conditions.

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Introduction

This work described herein is the development and testing of a thruster performance analysis system and serves in partial fulfillment of graduate thesis work for a Master's Degree at The University of Texas at El Paso (UTEP). The Center for Space Exploration Technology Research (cSETR), a NASA University Research Center (URC), started the development of a cryogenic propulsion system for diverse rocket testing applications. This system included the communications system for control of instrumentation inside the bunker facilities, as well as the development of a cryogenic propellant delivery system. The design and development of these systems was started by former students at the center, however little to no testing was conducted on them on the order of what is presented here.

Being a NASA URC, partnerships with NASA engineers exist for specific projects. One such project is the subject matter for this work, which is a collaborative NASA-UTEP effort started to test a cryogenic bi-propellant reaction control system (RCS) thruster. The thrusters, referred to hereafter as the "Pencil Thruster," were provided to the Center for performance testing, as well as design improvement based on performance analysis. The Pencil Thruster is a unique type of RCS thruster as it was developed or retrofitted using a design for an Aerojet engine igniter; hence, specific performance and design data was limited.

The introduction of a thruster experimental setup in the laboratory facilities of the University posed a new challenge for the Center as it introduced unique and new levels of safety and control requirements in order to meet thruster testing demands. The Pencil Thruster is a 35.6 N (8 lb_f) bi-propellant reaction control thruster, having liquid oxygen (LOX) and liquid methane (LCH_4) as its propellant combination.

In order to provide the propellant combination required, a methane condensation system was designed, developed, and tested prior to integration with the thruster test setup. A thrust measurement

system was also designed and both systems were designed to meet the Pencil Thruster requirements. Finally, a set of individual systems was integrated and tested with a fully-automated controls system.

Testing and validation of a previously designed LOX system, the design and development of a methane condensation system, as well as the development of a thrust measurement and an automation and control systems were all part of the work to be described in this paper. All of these efforts were done to provide a thruster performance analysis system. Preliminary integration and performance testing was conducted on these systems by firing the Pencil Thruster at two different test stages: one for a gas-gas propellant combination and another for liquid-liquid combination.

This thesis is divided into 7 chapters: the first 4 chapters exploring the individual subsystems (LOX, LCH4, thrust measurement, and automation controls) design and development, followed by an explanation of the integration of such systems as a unit, finalized with results and discussion, summary and conclusions, and future work pertinent to the project.

Chapter 1: Liquid Oxygen (LOX) Subsystem

The liquid oxygen (LOX) subsystem will be introduced in this chapter. A system description followed by the procedure used when preparing the delivery system will also be discussed.

1.1 Background and Introduction

The LOX delivery line, found in the bunker facilities of the Goddard laboratory in the college of Engineering at UTEP, was designed and developed by a former student from the Center [1]. 304 stainless steel ½"OD tubing was used as the propellant carrier. Cryogenic and LOX compatible valves and instrumentation were placed at different points in the propellant line. The system schematic as it was used for the Pencil Thruster setup is shown in Figure 1.1. A liquid methane (LCH_4) line was also designed though no production tank was ever included in the system. This line then served as a gaseous nitrogen purge for the experimental setup of the Pencil Thruster. The LOX and LCH_4 lines developed in the cSETR by former students contains the two main propellant feeds (red/green and blue respectively in Figure 1.1), with their respective liquid nitrogen (LN_2) line cooling supply and gaseous nitrogen purge. The LOX line is supplied via the use of a self-pressurized tank with 2 MPa (300 psig) pressure limitations. The line could only be subjected to 1.4 MPa (200 psig) as the relief valves were set to 1.4 MPa and solenoid valves are only rated to 1.6 MPa (230 psig).

In order to test the Pencil Thruster under liquid-liquid propellant combinations, the LOX line had to be validated and shown to be capable of delivering oxygen in its liquid form before injection to any test article. As mentioned before, the system was designed and assembled yet no testing or validation with liquid oxygen was done. Therefore validation experimental trials were conducted to analyze system cool-down characteristics. These trials provided a way to estimate line cool-down techniques and times to deliver oxygen in its liquid form. It is important to remember special storage, handling, and safety actions must be taken when dealing with LOX cylinders due to the volatile nature of the cryogen. [2]

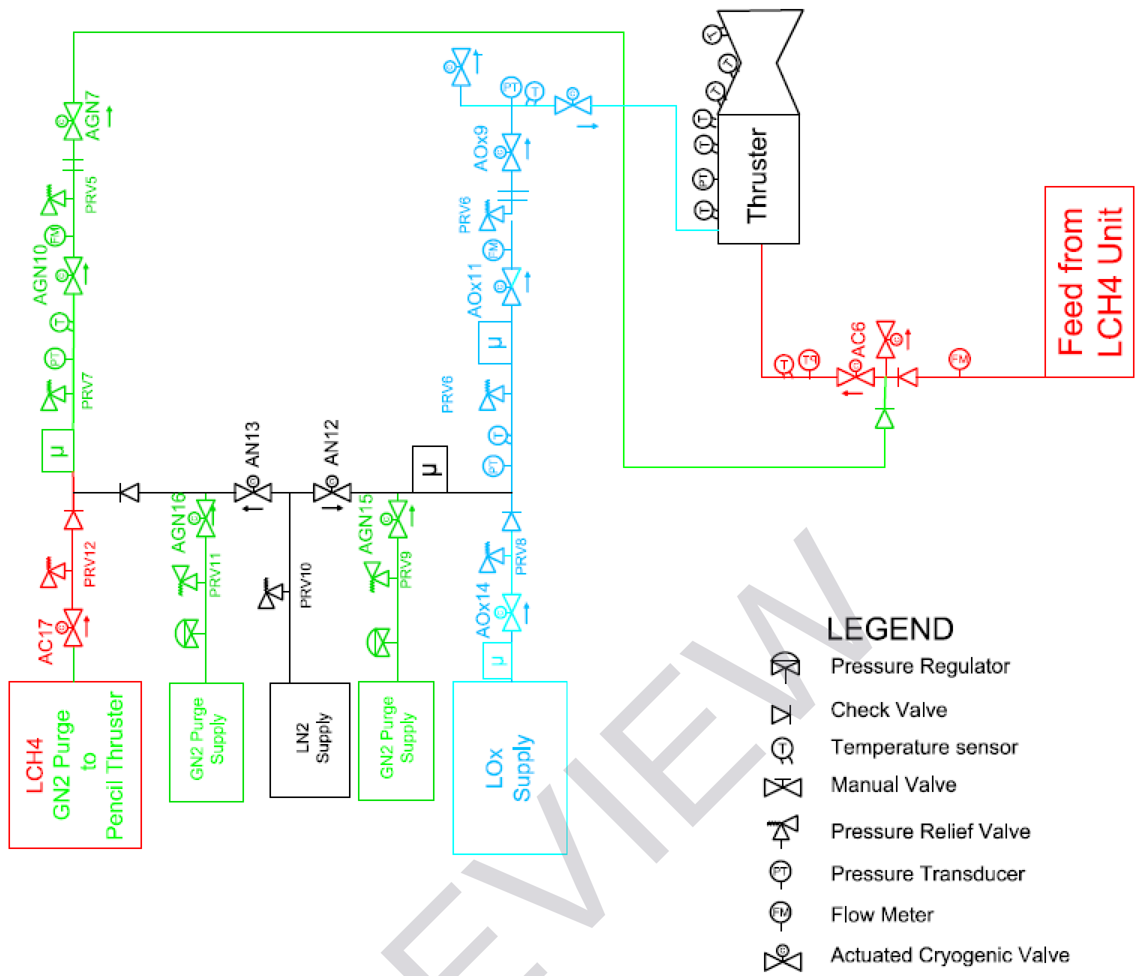

Figure 1.1: LOX Line Schematic

1.1.1 Cool-Down and Operating Procedure

In order to achieve liquid oxygen delivery to any test article, the delivery line and all of its components must be cooled to cryogenic compatible temperatures to avoid LOX gasification at any point in the line. Initial cool-down is done by flowing liquid nitrogen (LN_2) through the system. If the test article should not be cooled or restricts flow with holes smaller than 1/8" OD then a "bleed" valve must be positioned as close as possible to the test article in order to bring down line temperature of the delivery line. Fast (5-10 minutes) cryogenic cooling requires high flow rates. Therefore, whenever instrumentation having orifice size limitations is introduced to the system a by-pass line section must be added to speed the cooling process. In the case of the Pencil Thruster, combustion chamber injection

holes of 0.25 – 0.5 mm (0.01-0.02") in diameter were a limiting factor. As such, there was a need for the introduction of bleed valves in both propellant lines.

Once liquid nitrogen is seen coming out of the aforementioned valve, LN_2 may be run through the test article if needed and possible. It is important to mention that the user must cycle the bleed valve to avoid valve freezing. Even though all of the valves in the system are cryogenic rated, freezing was a common problem during the experimental procedures of the Pencil Thruster and valve cycling was determined to be an efficient way to avoid this phenomenon. Cycling repetition and timing is determined by the user's experience and familiarity with their system.

Once the desired temperature of the test article is reached, LN_2 flow may be halted and the system must continue to be cooled with oxygen. The user will notice a temperature increase upon start-up of LOX flow through the system, which is due to the fact that the oxygen is starting to flow from the tank. After a couple of minutes, the temperature should begin to drop again and the user should be able to see LOX coming out through the "bleed" valve and/or the test article. Steady state temperatures of -155 to -158 C (-247 to -252 F) were the target for this setup at an injection pressure of 100 to 150 psig (0.7 to 1 MPa).

Cool-Down Validation and Characteristics

A major requirement for appropriate testing was the characterization of line cool-down timing as well as validation of LOX flow at the end of the thruster assembly. Initial cool-down procedures for the line were initialized using liquid nitrogen (LN_2) flow, once liquid nitrogen was seen coming out of the thruster nozzle, LOX was now ran through the system. Both LN_2 and LOX were allowed to flow through the system, one at a time, by opening the bleed valve for the line, once a constant stream of liquid was seen coming out of the bleed, the thruster propellant valve was opened and the bleed valve was cycled.

Upon start-up of LOX flow, the temperature in the line raises due to the fact that LOX is now coming out of the tank and starting to flow. Figures 1.2 and 1.3 show the pressure and temperature data recorded during the cool-down and validation process of the LOX system. The intent of this validation

was to ensure proper functionality of the system, as well as to prove oxygen in its liquid form could be delivered to the thruster.

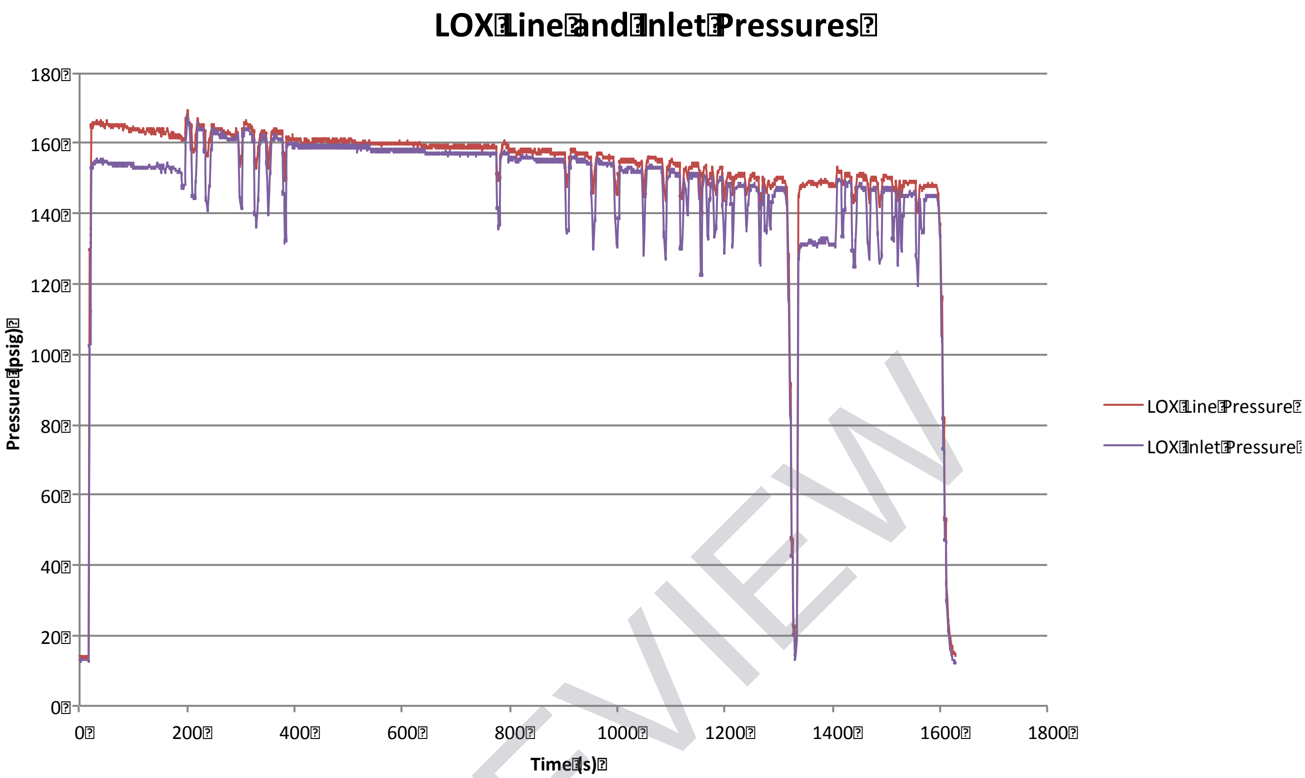

Figure 1.2 LOX Line and Inlet Pressures during cool-down validation

The pressure drops and rises correspond to user manipulation of valves (bleed and thruster) in the system, activating the flow of LOX through the line. It may be noted that these pressure drops correspond to a temperature drop as well, again indicating flow of LOX and cooling of the system. It will be discussed in the controls section that this process relies on the user's instinct and experience for appropriate system cool-down. Experimental trials showed repeatable cool-down behavior requiring 15-25 minutes for line cool-down time, starting from initial LN_2 flow and ending when LOX was seen coming out through the thruster's nozzle. Line pressure was measured at the middle section of the main propellant line, while inlet conditions were measured right before the thruster propellant valve.

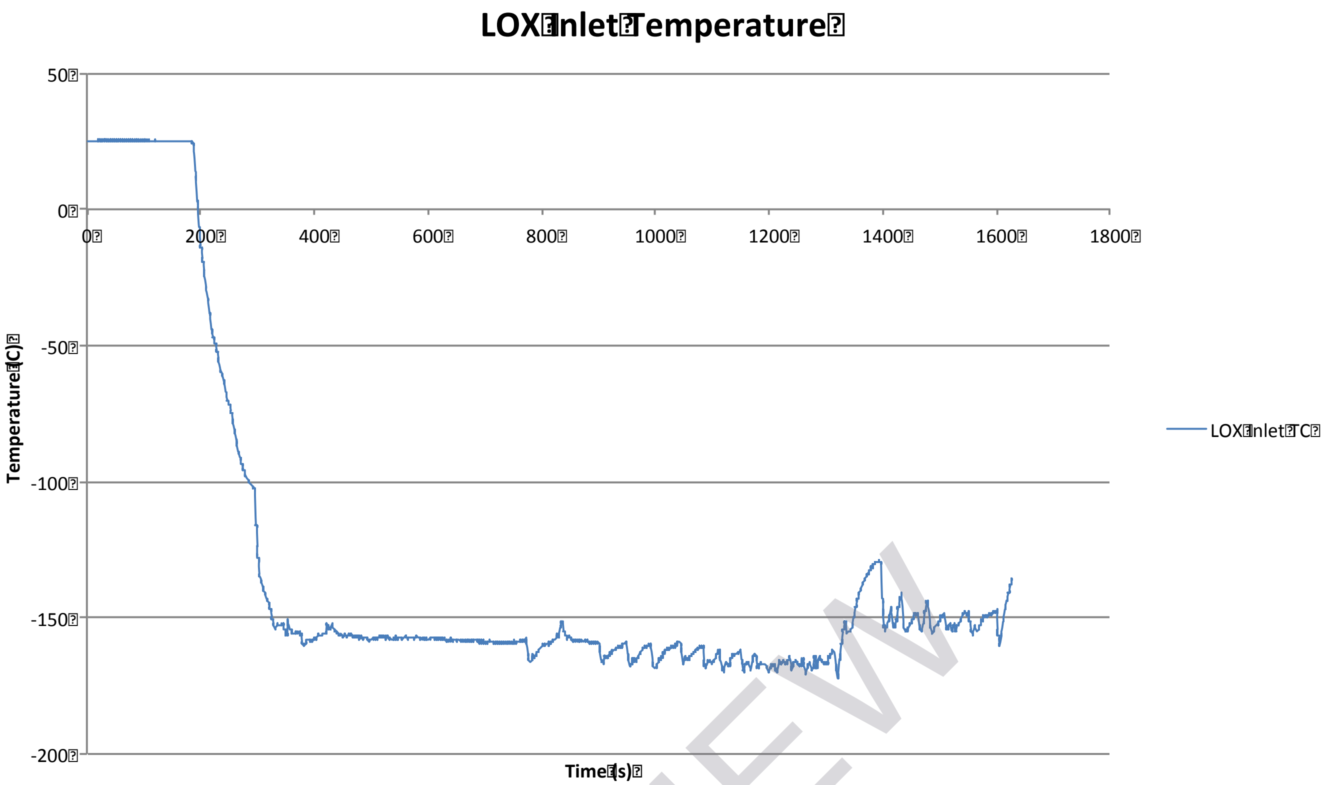

Figure 1.3 LOX Inlet Temperature