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Liquid Methane/Liquid Oxygen Injectors for Potential Future Mars Ascent Engines

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Introduction

Preliminary mission studies for human exploration of Mars[1] have been performed at Marshall Space Flight Center (MSFC). These studies indicate that for chemical rockets only a cryogenic propulsion system would provide high enough performance to be considered for a Mars ascent vehicle. Although the mission is possible with Earth-supplied propellants for this vehicle, utilization of in-situ propellants is highly attractive. This option would significantly reduce the overall mass of launch vehicles. Consequently, the cost of the mission would be greatly reduced because the number and size of the Earth launch vehicle(s) needed for the mission would decrease. NASA/Johnson Space Center has initiated several concept studies[2] of in-situ propellant production plants. Liquid oxygen (LOX) is the primary candidate for an in-situ oxidizer. In-situ fuel candidates include methane (CH_4), ethylene (C_2H_4), and methanol (CH_3OH).

MSFC initiated a technology development program for a cryogenic propulsion system for the Mars human exploration mission in 1998. One part of this technology program is the effort described here: an evaluation of propellant injection concepts for a LOX/liquid methane Mars Ascent Engine (MAE) with an emphasis on light-weight, high efficiency, reliability, and thermal compatibility. In addition to the main objective, hot-fire tests of the subject injectors will be used to test other key technologies including light-weight combustion chamber materials and advanced ignition concepts.

This paper will address the results of the liquid methane/LOX injector study conducted at MSFC. A total of four impinging injector configurations were tested under combustion conditions in a modular combustor test article (MCTA), equipped with optically accessible windows. A series of forty hot-fire tests, which covered a wide range of engine operating conditions with the chamber pressure varied from 320 to 510 and the mixture ratio from 1.5 to 3.5, were performed. The test matrix also included a variation in the combustion chamber length for the purpose of investigating its effects on the combustion performance and stability.

MAE Injector Design

1) Baseline Engine

The goal of this project is to provide the injector technology for developing a cryogenic propulsion system that will meet the requirements of the planned Mars sample return (MSR) mission[3]. The original intention was to offer a mission option that incorporates in-situ propellant production and utilization for the ascent stage. Such an option has been carefully considered as a subscale precursor to a future human mission to Mars. A propulsion system study[5] conducted at MSFC has shown that a pressure-fed system is suitable for a cryogenic ascent stage for the MSR mission. This system was selected based on several factors including weight minimization, packaging efficiency, and operational simplicity. While a regulated pressurization system is planned for the first-stage of the Mars Ascent Vehicle, a blow-down pressurization system is baselined for the second-stage.

Table 1 summarizes key MAE operating conditions derived from the MSFC system study. The injector technology program uses the data shown in the third column as baseline design conditions. The last column of Table 1 shows a range of operating conditions for the blow-down situation. Both the LOX ($P_{critical}$=731 psia) and liquid methane ($P_{critical}$=668 psia) are in the subcritical pressure regime throughout the expected range of chamber pressures.

2) Injector Configurations

Jet impinging injectors have commonly been used in LOX/liquid hydrocarbon rocket engines. For small rocket engines, triplet and unlike-impinging configurations are widely employed. Typically they provide higher performance than other configurations such as like-on-like impingement and shower-head. In this study, a split-triplet (F-O-O-F) arrangement, which was introduced by Pavli,[6] has been selected as the baseline. This configuration, as shown in Figure 1, is similar to a conventional triplet (F-O-F) impinger; the only difference is an additional oxidizer orifice on the split-triplet for reducing the disparity between the fuel and oxidizer orifice sizes. This arrangement is suitable for the MAE since the baseline O/F mixture ratio is 3.

An unlike-doublet (F-O) was selected as an alternative configuration. At first glance, this configuration resembles the split-triplet, if two unlike-doublet elements are arranged on the injector face with a back-to-back position, (F-O) and (O-F). However, this unlike-doublet grouping may result in an oxygen-rich region between the two injection elements. To avoid this situation, the elements, as shown in Figure 2, are oriented on the injector face as (F-O) and (F-O).

Because the MAE is relatively small, full-size injectors (2.4-inches in diameter) have been designed and fabricated. Injectors were designed to achieve the objectives of light weight and high performance while ensuring thermal compatibility and combustion stability. In order to optimize the manifold system and assure a uniform mass distribution, the injection elements are equally distributed in the circumferential direction. For the split-triplet, only a single ring of injection elements fit into the injector. On the other hand, two rings of unlike impinging elements fit in the injector face. In all cases the outermost ring of orifices injects fuel in order to prevent an oxygen-rich environment near the chamber walls.

A total of ten versions of the two basic injector configurations were designed and fabricated. Variations in the impinging height, impinging angle, orifice size, and injection element arrangement, as shown in Table 2, are utilized in these injector face designs. For the unlike doublet injectors (F-O-F-O), an oxygen-rich condition may exist at the centerline region of the injector face. To minimize this condition, the fuel orifices on the inner element ring are canted at an angle in the radial direction (Figure 2). This orientation permits fuel to penetrate into the core region to provide additional propellant mixing. Several cant angles, as listed in Table 2, were also incorporated in the design. Although ten injector configurations were designed, only the injector # 1, 2, 6, and 10, as labeled in Table 2, were tested and reported in this paper,

3) Combustion Instability

A reduction in pressure drop (ΔP) across an injector face will result in a lower tank pressure requirement which in turn will reduce the overall propulsion system weight. The desire to reduce propulsion system weight must be balanced with the need to provide adequate injector ΔP to ensure combustion stability. Lower ΔP values may violate the chug margin and cause combustion instabilities.

Injector orifices were sized primarily based on combustion stability considerations. To size fuel orifices, Hewitt's correlation[7] has been employed to scale injector configurations from Pavli's data.[6] Oxidizer orifice sizes were selected to be similar to the fuel orifices, while keeping their momentum ratio very close to the values at optimum mixing. In addition, several acoustic cavity tuning blocks have been designed to accommodate two quarter-wave acoustic cavity sizes, 0.5" and 1" in depth. The test series covered combustion conditions for the cases with and without the tuning blocks. The chamber pressure fluctuation was less than 3% for all testing conditions.

Test Hardware and Facility

1) Test Hardware

The test hardware includes the MSFC Modular Combustion Test Article (MCTA), and the injector hardware built specifically for this program. The MCTA , as shown in Figure 3, is a "workhorse" combustion chamber. It is composed of several modules, which are held together by four high-strength tie rods. The copper throat section contains drilled passages for counterflowing cooling water. The cylindrical portion of the 4-inch diameter chamber consists of several modules, including a window module and an igniter/instrumentation module. The window module provides optical access to the chamber for photographing the flowfield or for performing non-intrusive optical diagnostics. There are several ports in the igniter/instrumentation module, one of which is used for a conventional gaseous hydrogen/gaseous oxygen torch igniter system. Pressure transducers and thermocouples may be installed into other ports in this module. The length of the combustion chamber can be altered by inserting blank modules of various lengths.

The injector assembly consists of an annular injection ring, an acoustic cavity tuning block, and a main injector. Nitrogen was used as a film coolant along the chamber wall through a series of small orifices in the annular injection ring. A space between the annular injection ring and the main injector will serve as an acoustic cavity to enhance combustion stability. Different cavity configurations can be tested by changing tuning blocks. The main injector will flow liquid methane and liquid oxygen into the combustion chamber. The injector face, which is made of copper, is brazed to a manifold that has several concentric channels to distribute the propellants.

2) Test Facility

Injector testing was conducted at Test Stand 115 in MSFC's East Test Area. This open-air test position includes a digital control system, analog and digital data acquisition systems, and cameras for recording video and high-speed film. A semi-trailer is used to house lasers, computers, and other combustion diagnostics equipment. This trailer provides a controlled environment for the equipment in close proximity to the test article.

Propellants can be provided at a variety of conditions at Test Stand 115. For the MAE program, LOX is supplied from a 500 gallon run tank at pressures up to 3000 psi. Liquid methane is stored in a 2200 gallon vacuum-jacketed vessel. A foam-insulated fuel run tank having a capacity of 20 gallon at 3000 psi was used in this test program.

High pressure gases are available on the test stand for purging and pressurization (helium and nitrogen) and for igniter propellants (oxygen and hydrogen). De-ionized water for cooling the MCTA throat section is supplied from a 500 gallon, 3000 psi tank.

Preliminary Assessment of Results

A total of forty hot-fire tests on four injector configurations were successfully conducted in this project. The test matrix covered various test conditions as shown in Table 3. There was not any indication of the overheating on the injector faces. Preliminary data reduction showed that the injectors provided stable combustion under all operating conditions. Combustion efficiency of the subject injectors is ranged from 92% to 110%. Detailed data reductions of the test results are underway.

Raman scattering signals of the combustion species were measured using an excimer laser. The results showed that the species concentration was uniformly distributed in the region of the measurement. In addition to the laser diagnostic, an infrared camera was used to record visuals of the combustion flow field. These images depicted clearly the injection propellant jets and the circulation in the injector face region.

Acknowledgments

The author would like to acknowledge the contributions of a number of MSFC personnel and contractors on this project. The hot-fire tests were not successfully executed without the technical consultation of John Cramer. Andy Hissam, Kevin Baker, and Mike Shadoan have dedicated their efforts to the design and fabrication of the MCTA and the injector hardware. Cynthia Lee and her test team have labored many hours to prepare the test facility and to perform the hot-fire tests. Marvin Rocker has performed stability analysis for the MAE injectors designs. David McDaniels, Herbert Zollar, Hai Nguyen and Jeff Lin have conducted cold-flow tests, thermal analyses, and combustion analyses, respectively. Finally, Dr. Joseph Wehrmeyer of Vanderbilt University and Perry Gray of Micro Craft

Incorporate have spent numerous time to perform combustion measurements with the laser diagnostic and the infrared camera, respectively.

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Table 1: MAE Operating Conditions

Parameter	Unit	Baseline	Range
Chamber Pressure	Psia	250	100 - 550
Mixture Ratio		3	(N/A)
Thrust	Lbf	600	300 - 1000
Vacuum Specific Impulse	Second	346	(N/A)
Exit/Throat Area Ratio		100	(N/A)
Mass Flow Rate	Lbm/sec	1.86	0.86 - 2.87

Table 2: Injector Configurations

No.	Injector Type	Config.	Orifice Dia. LOX (in)	Orifice Dia. CH4 (in)	Cant Angle (deg)
1	SPLIT TRIPLET	F-OO-F	0.042	0.03	(N/A)
2	UNLIKE DOUBLET	F-O-F-O	0.05	0.035	NO
3	UNLIKE DOUBLET	F-O-F-O	0.05	0.035	YES
4	UNLIKE DOUBLET	F-O-F-O	0.05	0.035	YES
5	UNLIKE DOUBLET	F-O-O-F	0.05	0.035	NO
6	UNLIKE DOUBLET	F-O-F-O	0.042	0.03	YES
7	SPLIT TRIPLET	F-OO-F	0.042	0.028	(N/A)
8	UNLIKE DOUBLET	F-O-F-O	0.042	0.03	YES
9	UNLIKE DOUBLET	F-O-F-O	0.046	0.032	YES
10	SPLIT TRIPLET	F-OO-F	0.046	0.034	(N/A)

Table 3: Test Conditions

PARAMETERS	RANGE
Chamber Pressure (psi)	320 -> 530
Mixture Ratio	1.5 -> 3.5
Test Duration (sec)	5 -> 15
Mainstage Duration (sec)	0.25 -> 10
Chamber Length (in)	9 and 13

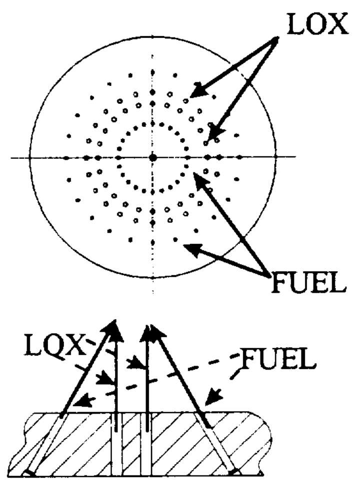

Figure 1: Split Triplet Injector (F-OO-F)
(a) Injector Face, (b) Injection Element

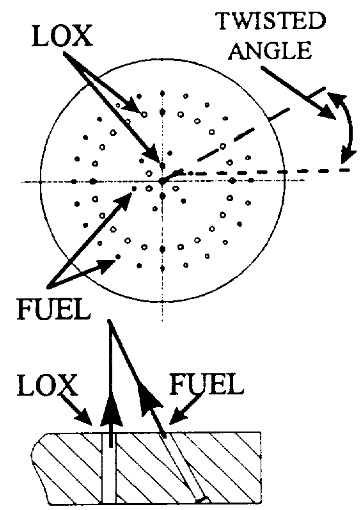

Figure 2: Unlike doublet Injector (F-O-F-O)
(a) Injector Face, (b) Injection Element

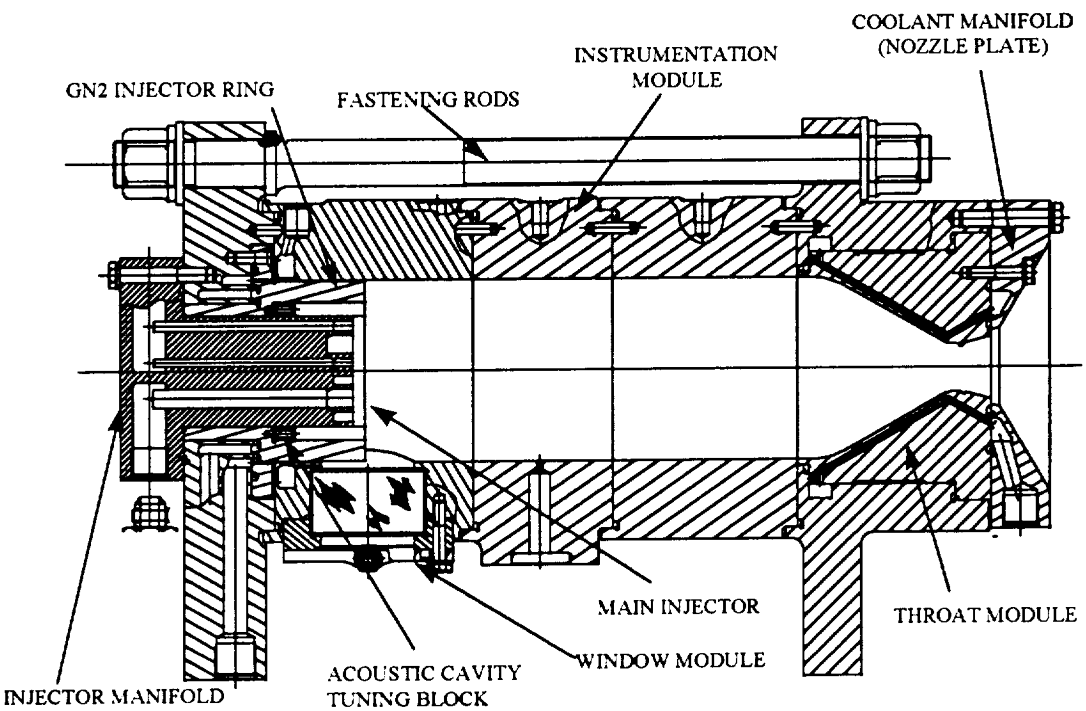

Figure 3: MCTA with an Injector Assembly

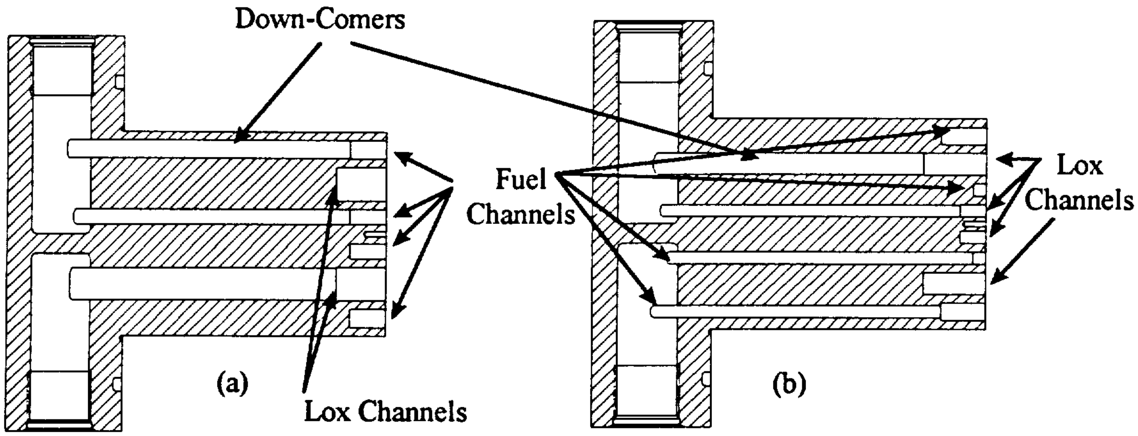

Figure 5: Injector Cores of Impinging Injectors, (a) Unlike-Doublet (F-O-F-O)
(b) Split-Triplet (F-OO-F) and Unlike-Doublet (F-O-O-F)