Design and Study of a LOX/GH₂ Throttleable Swirl Injector for Rocket Applications

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ABSTRACT

A LOX/GH₂ swirl injector was designed for a 10:1 propellant throttling range. To accomplish this, a dual LOX manifold was used feeding a single common vortex chamber of the swirl element. Hot-fire experiments were conducting for rocket chamber pressures from 80 to 800 psia at a mixture ratio of nominally 6.0 using steady flow, single-point-per-firing cases as well as dynamic throttling conditions. Low frequency (mean) and high frequency (fluctuating) pressure transducer data, flow meter measurements, and Raman spectroscopy images for mixing information were obtained. The injector design, experimental setup, low frequency pressure data, and injector performance analysis will be presented. C* efficiency was very high (~100%) at the middle of the throttleable range with somewhat lower performance at the high and low ends. From the analysis of discreet steady state operating conditions, injector pressure drop was slightly higher than predicted with an inviscid analysis, but otherwise agreed well across the design throttling range. Analysis of the dynamic throttling data indicates that the injector may experience transient conditions that effect pressure drop and performance when compared to steady state results.

INTRODUCTION

With the latest drive by NASA and the industry to reduce costs for access to space, future vehicle designs are moving towards reduced number of stages and engines. This requires liquid rocket engines (LRE) to reduce thrust to maintain optimum acceleration for an entire orbital insertion. Future vehicle concepts may even have the main engine provide thrust for final orbital insertion, atmospheric reentry, and landing. Also, rocket-based combined cycle propulsion, with a potential for reusability with little turnaround time between flights, is intensely being researched at this time. The LRE of the future will be required to provide more efficient thrust, perform longer, and operate across a wider throttling range.

Current liquid rocket engines rarely have been designed beyond a 2:1 throttling range. Huge penalties due to nonlinear pressure drop increases with propellant flowrate result when designing a throttleable LRE with today's prevailing designs. This investigation sought to demonstrate an injector capable of deep (• 5:1) throttling without unreasonable pressure drop penalties and without the use of moving parts in the injector.

Research Objectives

The objectives for this research program are as follows:
- Design a swirl injector for LOX/GH₂ for a mixture ratio of 6 and a throttleable chamber pressure range goal of 10:1 (from 1000 to 100 psi).
- Conduct hot-fire experiments to characterize the performance of the injector across the throttleable range.
- Evaluate the following:
  - Uni-element C* efficiency over the throttleable range.
  - Uni-element chamber combustion stability with the injector over the throttleable range (not presented in this paper, see Final Report[1]).
  - Uni-element mixing over the throttleable range at one chamber axial location using Raman spectroscopy (not presented in this paper, see Final Report[1]).

Research Approach

The concept of a 10:1 throttleable swirl injector was originally created during the tenure of guest researcher Professor Vladimir Bazarov from Moscow Aviation Institute in Russia. Professor Bazarov's conceptual designs for throttling liquid-liquid injectors were modified and sized for a 10:1 throttling LOX/GH$_2$ injector. A completely new injector assembly and manifold were created for the existing PSU two-inch square, windowed combustion chamber. To conduct these experiments across the full throttling range, a LOX/LN$_2$ heat exchanger was also designed and installed just upstream of the injector to provide better quality LOX, particularly for low flowrate conditions (< 0.3 lbm/s).

The first phase of this program was to obtain steady state, single point case conditions across the throttling range. During these steady state tests, the injector was characterized for pressure drop, combustion efficiency, and stability. To evaluate mixing in-situ, Raman spectroscopy data was acquired. The second phase involved adding a continuous throttling capability to the Cryogenic Combustion Laboratory so that propellant flowrate could be varied during a single run. The purpose of this was to verify the throttling capabilities of this injector under more realistic dynamic conditions. Raman spectroscopy data were not acquired during the dynamic throttling experiments.

THROTTLEABLE INJECTOR DEVELOPMENT FOR LOX/GH$_2$

The goal for this research was to design a throttleable injector using LOX/GH$_2$ with a throttleable range of 10:1. The design criteria for this throttleable injector were as follows:
- Mixture ratio of LOX to GH$_2$ of six (O/F = 6).
- LOX mass flow rate from 0.1 to 1.0 lbm/s. GH$_2$ mass flow rate from 0.0167 to 0.167 lbm/s.
- Chamber pressure from 1000 down to 100 psia.
- Pressure drop for LOX across the injector following the profile in Figure 1 where TA is the total inlet area of the injector.
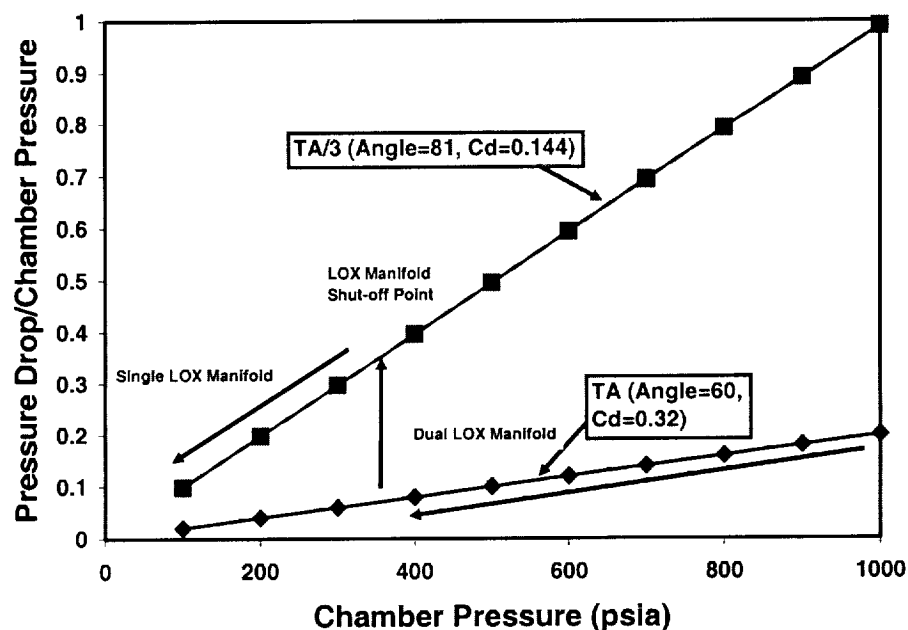

Figure 1: LOX swirl injector pressure drop characteristics for single and dual LOX manifold operation.

There are three key parameters a designer can manipulate in a tangential orifice swirl injector to obtain the desired swirl characteristics of spray angle, pressure drop, and discharge coefficient [2,3,4,5]. These parameters are the inlet area (governed by r_o and i, the number of inlets), the swirl chamber radius (R), and the nozzle exit radius (r_c) as shown in Figure 2.
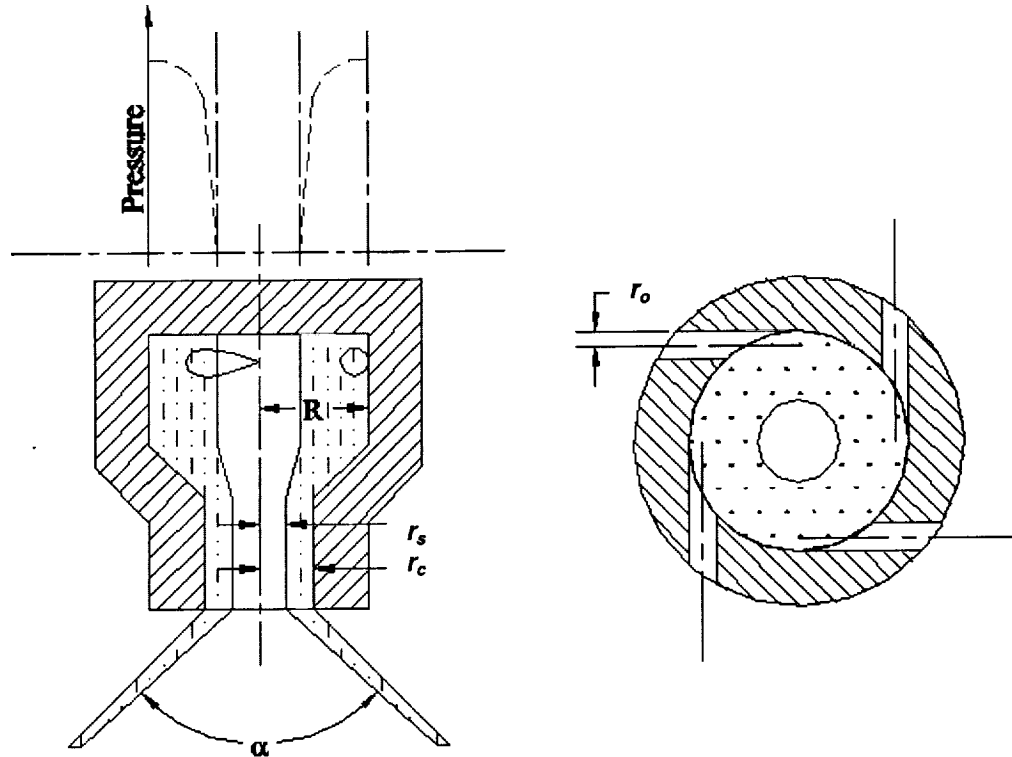

Figure 2: A Generic, tangential orifice swirl injector with inlet passage radius (r_o), swirl chamber radius (R), and nozzle exit radius (r_c).

A fundamental property of a swirl injector is that it can operate at different discharge coefficients (Cd) to accommodate a range of vortex chamber mass flow rates. Thus a single injector element could be used to cover the entire throttling range. However, the tangential inlet area fixes a particular Cd. To circumvent this problem, it was decided to use dual inlet circuits for the LOX flow. A schematic representation of this method is presented in Figure 3.
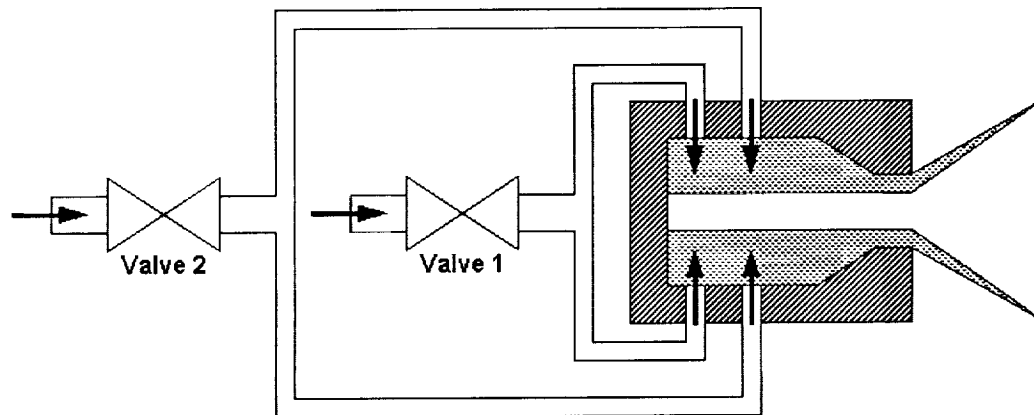

Figure 3: Conceptual swirl injector design with two inlet manifolds controlled by upstream valves.

At high throttle, Valves 1 and 2 are open. At a prescribed low throttle position (e.g., 350 psia in Figure 1), Valve 2 closes, decreasing the tangential orifice inlet area and hence mass flow, causing a change in the swirl flow with a lower discharge coefficient. Note that it was only necessary to design a dual circuit element for LOX since the fuel enters the injector as a gas. The $\Delta P/P_c$ for a gaseous injector is essentially constant with throttling because the density changes proportionally with pressure[6]. Therefore, only the LOX swirl element utilized the valve manipulation of its inlet area. Although not necessary for throttling capability, an effort was made to also investigate a coaxially swirled gaseous hydrogen element to gain insight into the effect of swirled versus un-swirled coaxial GH_2 on swirled LOX atomization.

Liquid Oxygen (LOX) Injector Element

The first step to designing this injector was to find the necessary inlet area for the two LOX stages. One requirement was that at the minimum throttle condition, the pressure drop across the injector should not fall below about 8% of the chamber pressure to maintain low frequency stability margin. Another was that at the full-throttle point, the pressure drop across the injector should not exceed 20% of the chamber pressure to keep pump requirements manageable.

To establish the correct effective inlet area of the injector for approximating the throttling profile in Figure 1, the low throttle condition, when only LOX Manifold 1 is in operation, needed approximately a third of the total effective inlet area (TA/3). When both manifolds are open at the high throttle condition, the total effective inlet area (TA) is obtained. Therefore, the LOX injector element inlet orifices fed by LOX Manifold 2 had to have approximately twice the inlet area as the inlet orifices fed by LOX Manifold 1.

Existing hardware was used when possible, and so some of the confining dimensions were already determined by mating requirements of rocket chamber hardware already on hand. This particular injector assembly was designed as an evolution of the work of Professor Vladimir Bazarov performed as a guest researcher at The Pennsylvania State University. The injector assembly design for this program adapted from prior efforts is shown in Figure 4.
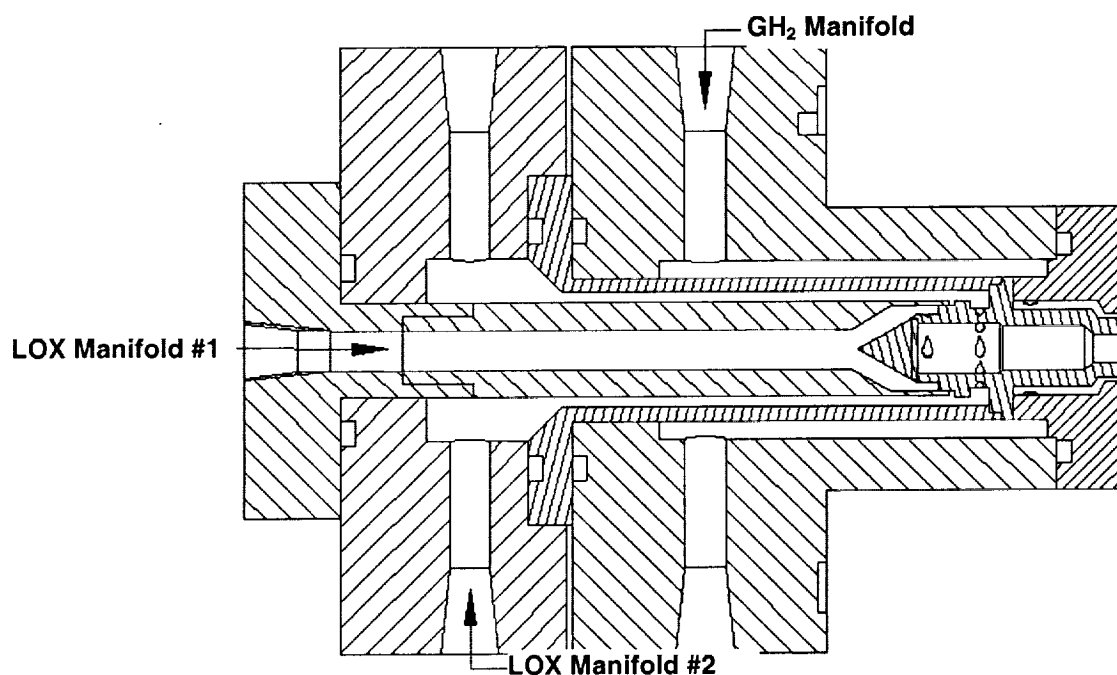

Figure 4: Throttleable LOX/GH₂ injector assembly.

For the higher flowrate cases, a swirl angle of approximately 60° was chosen as a reasonable compromise between rapid atomization/mixing and near-injector heat flux. This swirl angle was used successfully in previous PSU research for conventional swirl coaxial injectors. From the throttling profile in Figure 1, the desired discharge coefficient for the high-throttle region needed to be approximately 0.32 to produce a swirl angle of 60°. To produce the desired pressure drop, the low-throttle profile required a Cd of approximately 0.144 with a swirl angle of 81°. The injector nozzle exit diameter (2 * r_c) was determined from hydraulic swirl theory[1] to be 0.228 inches (0.579 cm).

To obtain the prescribed effective inlet areas corresponding to Figure 1, the first set of inlet orifices (fed by LOX Manifold 1) is comprised of three, 0.067 inch (1.70 mm) diameter holes and the second set of inlet orifices (fed by LOX Manifold 2) is comprised of six, 0.0625 inch (1.59 mm) diameter holes. This does not strictly adhere to the total inlet area for the low-pressure throttling profile being a third of the total inlet area for the high-pressure throttling profile (actually, TA_{Low} / TA_{High} = 0.383), but it is suitable to produce the injector and pressure drop characteristics as presented in Figure 5. The final LOX swirl injector design is provided in Figure 6.
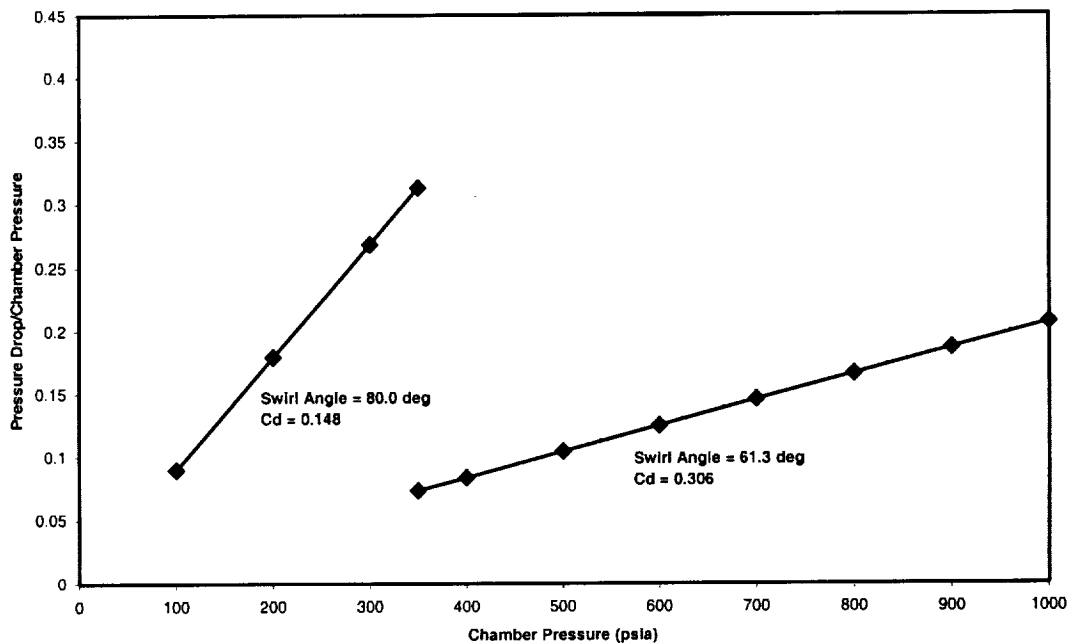

Figure 5: LOX swirl injector pressure drop characteristics at r_c = 0.114 inches.
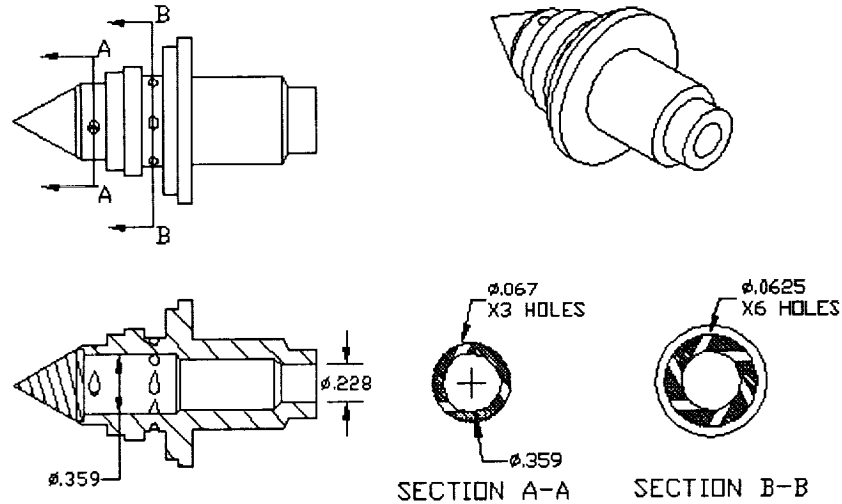
Figure 6: Final LOX swirl injector element design.

Gaseous Hydrogen (GH₂) Injector Plate

The injector plate is designed to fit coaxially around the LOX injector element with the hydrogen flow restricted at the coaxial nozzle to provide the desired pressure drop. As previously stated, the variable Cd capability of a swirl injector is not required for the GH₂ injector plate since the $\Delta P/P_c$ for a gaseous injector is essentially constant with throttling. Since the injected hydrogen flow is not swirled, it enters the combustion chamber in a cylindrical axially directed flow intersecting the conical LOX flow. The shear GH₂ flow eventually mixes with the expanding LOX as depicted schematically in Figure 7.
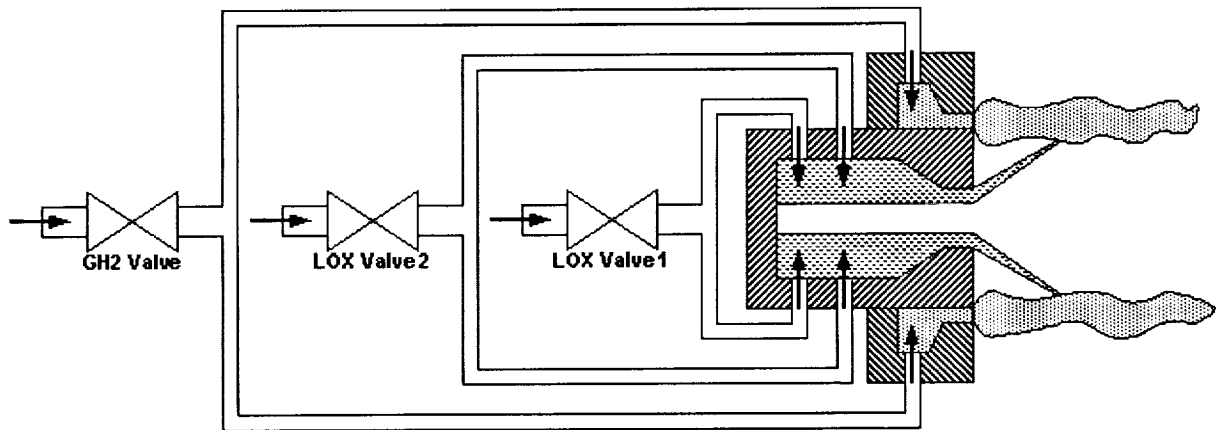

Figure 7: Conceptual design of the swirl injector assembly.

The nozzle gap of 0.035 inches (0.89 mm) between the converging GH₂ injector plate exit diameter and the exterior case of the LOX injector element was designed to satisfy a $\Delta P/P_c \cong 0.1$. GH₂ radially enters the annulus upstream of the coaxial nozzle through twelve subcritical channels formed by a standard drill bit of 0.1015 inches (2.58 mm) diameter. A drawing of the shear GH₂ injector plate is shown in Figure 8.
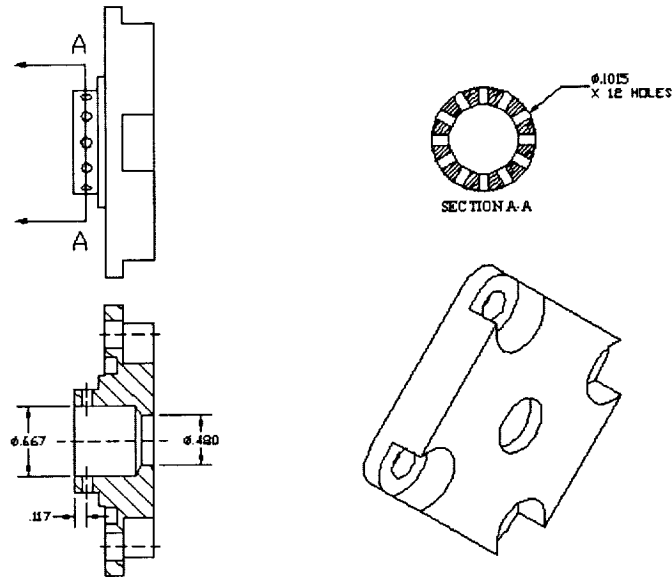
Figure 8: Shear flow GH₂ injector plate.

To augment the primary investigation of a "standard" swirl coaxial injector, a GH_2 co-swirling injector plate was designed and tested under combusting conditions to investigate any performance change due to swirling the GH_2 flow as well as the LOX. The swirl flow for this design was physically restricted by the LOX injector element located along the center axis. The outer diameter of the LOX injector at the coaxial exit is 0.41 inches (10.4 mm). Assuming incompressible flow due to the low velocity of GH_2 and using hydraulic theory as if a liquid, it was calculated that a swirl chamber radius (R) of 0.262 inches (6.65 mm) and a coaxial annulus exit outer diameter of 0.480 inches (12.19 mm) would provide a desirable $\Delta P/P_c = 0.09$ and swirl angle of 40°, assuming no momentum dissipation. This swirl angle was designed to be smaller than the LOX swirl angle to ensure interaction between the coaxial propellants cones, with considerable margin given the application of liquid swirl theory to the gaseous propellant. A drawing of the co-swirled GH_2 injector plate is shown in Figure 9.
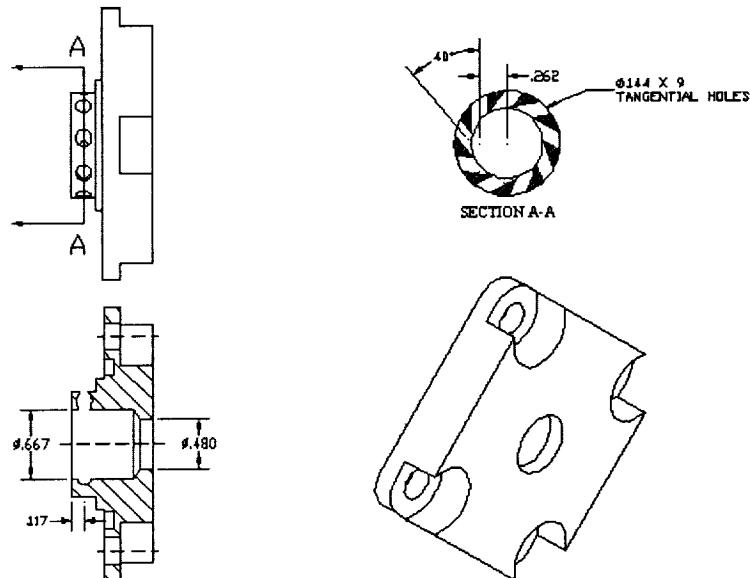

Figure 9: Co-swirled GH₂ injector plate.

EXPERIMENTAL SETUP

The Facility

Hot-fire experimentation was performed at the Propulsion Engineering Research Center's Cryogenic Laboratory at The Pennsylvania State University. This facility has the capacity to supply up to 1 lbm/s (0.45 kg/s) of LOX from a high-pressure run tank. Gaseous hydrogen is supplied from K-bottle clusters providing up to 0.25 lbm/s (0.11 kg/s) at 2400 psia supply pressure. Along with LOX and GH_2, the facility is also capable of supplying hydrocarbon fuel such as RP, JP, and ethanol. The facility is composed of a reinforced concrete test cell with two test stands, one on the ground floor and one on an upper tier, both run by a single control center. Currently, the upper test stand is configured for RBCC rocket/ejector studies and the lower for conventional rocket combustion studies like this particular project.

Test Matrix

Six discreet cases were targeted to explore the capabilities of this throttleable swirl injector. These cases were picked based upon criteria of effective demonstration of throttling and LOX manifold manipulation while considering facility limitations. The test matrix is presented in Table 1.

Table 1: Targeted Test Matrix

Case	1a-2	1b-2	1c-2	2-2	3-2	4-2
Chamber Press. (psia)	350	350	350	700	100	1000
Nozzle Throat Dia. (in.)	0.006	0.006	0.006	0.006	0.006	0.006
OXIDIZER SUPPLY:						
LOX Manifolds	1	1&2	1&2 to 1	1&2	1	1&2
LOX Flowrate (lbm/s)	0.35	0.35	0.35	0.70	0.10	1.00
FUEL SUPPLY:						
GH_2 Flowrate (lbm/s)	0.0583	0.0583	0.0583	0.1167	0.0167	0.1667
PURGE SUPPLY:						
GHe Flowrate (lbm/s)	0.006	0.006	0.006	0.008	0.003	0.010

EXPERIMENTAL RESULTS

Steady State, Single Point Cases

This research program successfully tested the throttleable swirl injector for approximately 900 seconds of steady state hot-fire. The $\Delta P/P_c$ results from the experiments are presented in Figure 10 along with the projected throttling profile from Figure 5 for reference. In general, the results exhibit a throttling profile consistent with the inviscid-theory-derived projection with the actual $\Delta P/P_c$ being slightly higher than predicted.
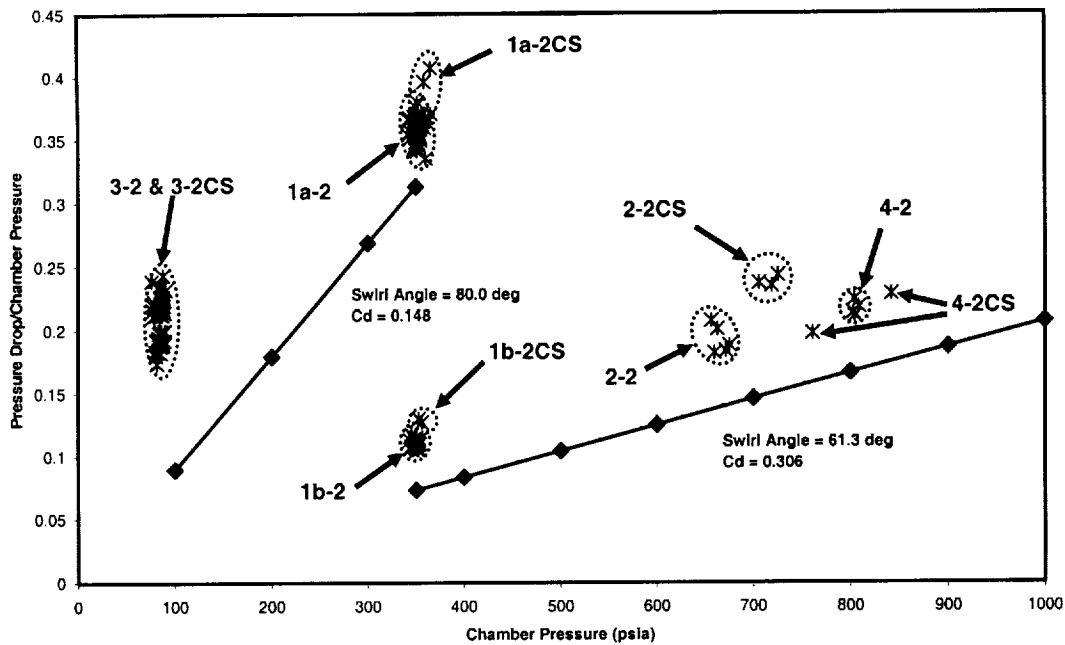
Figure 10: LOX swirl injector pressure drop design characteristics with hot-fire test results.

Table 2 provides an abbreviated summary of average experimental results. The unabridged experimental result summary can be found in the final report[1].

Table 2: An Abbreviated Summary of Average Experimental Results

Case	P_c (psia)	ΔP (psid)	LOX $\Delta P/P_c$	Mixture Ratio	C^* (ft/s)	C^* Efficiency	Comments
3-2	85	18	0.216	5.85	5965.0	78.03%	
1a-2	352	126	0.358	6.08	7636.7	99.71%	
1b-2	349	39	0.110	6.00	7571.4	98.62%	
1a-2CS	363	142	0.391	6.19	7898.6	102.42%	
1b-2CS	354	46	0.129	5.90	7698.5	99.51%	
2a-2CS	611	422	0.690	6.07	7091.3	92.39%	Test #9, 4/23/01 & Test #3-5, 4/24/01
2a-2CS	663	415	0.626	6.06	7415.3	96.53%	Test #6-11, 4/24/01
2-2	665	128	0.192	6.38	7340.1	96.65%	
2-2CS	717	171	0.238	6.68	7616.6	101.38%	
4-2CS	761	150	0.197	4.83	7634.6	102.31%	Test #12, 4/24/01
4-2	805	174	0.217	6.79	6376.2	84.07%	
4-2CS	842	192	0.228	7.21	6077.7	81.53%	Test #13, 4/24/01

Figure 11 presents the characteristic exhaust velocity (C^*) trend. The injector runs at higher C^* efficiency at the middle of the designed operating range and deviates from the theoretical C^* at the low and high range. It was anticipated that atomization and mixing would be enhanced with higher pressure combustion; however, it is possible that the higher gas-to-liquid momentum ratio at higher pressures actually collapses the LOX cone at some point and impedes atomization and mixing. The momentum angle for the combined propellant flows at Pc = 700 psia is approximately half its value at Pc = 350 psia where it is about 8° (half angle), with both LOX manifolds operating. At low throttle conditions, the LOX injector pressure drop may be too small to ensure good atomization for high efficiency operation. Also, at the minimum throttle condition, feed-coupled instability was evident; it's possible that this had a detrimental effect on C^* efficiency. See Santoro[1] for a complete discussion of these

stability issues. Note that the feed-coupled instability was a result of facility and operational issues for these experiments and not a product of injector design.
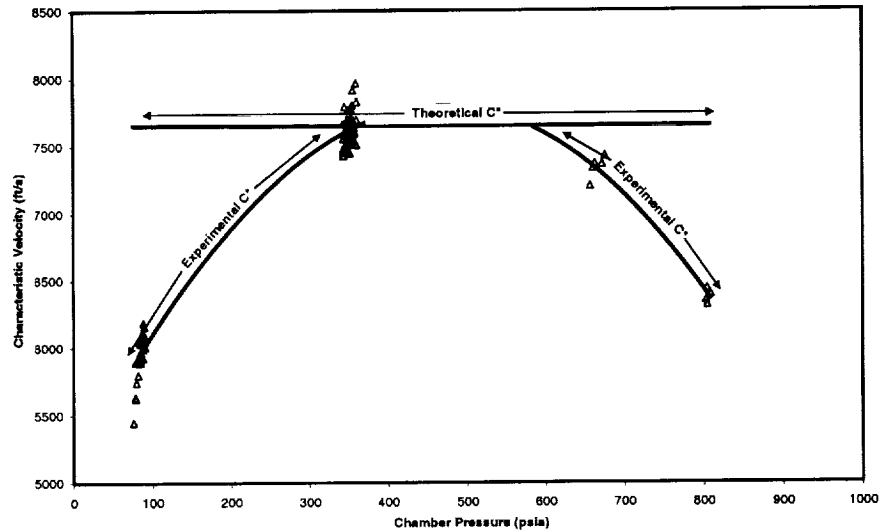

Figure 11: Swirl injector characteristic velocity (C*) data and trends for swirl LOX injector and the shear GH$_2$ injector plate.

An effort was made to evaluate the influence a co-swirling GH$_2$ injector plate would have on performance compared to the GH$_2$ shear plate. Figure 10 and Table 2 illustrates the shift in characteristic exhaust velocity and $\Delta P/Pc$ using the co-swirling GH$_2$ injector plate ("CS" signifies co-swirling). The data indicates that the co-swirling GH$_2$ injector plate provided an enhancement in C* and C* efficiency. This is apparent when comparing the co-swirling cases 1a-2CS, 1b-2CS and 2-2CS with their hydrogen shear flow counterparts 1a-2, 1b-2 and 2-2. The data suggests that the co-swirling GH$_2$ injector plate is providing better mixing. To better illustrate the improvement in C* efficiency, the theoretical and experimental C* data and trends using the co-swirling GH$_2$ injector plate is presented in Figure 12.
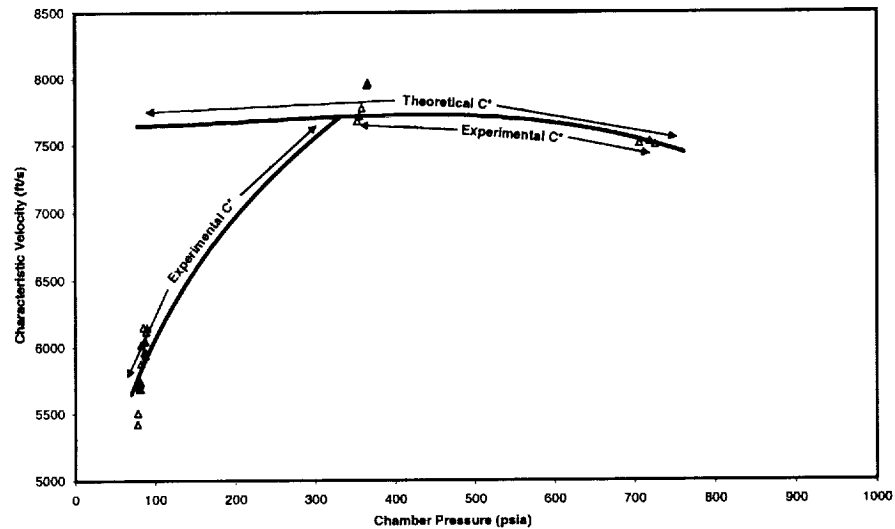

Figure 12: Swirl injector characteristic velocity (C*) data and trends for swirl LOX injector and the co-swirling GH$_2$ injector plate.

Dynamic Throttling

     A dynamic throttling system was developed and implemented in the Cryogenic Combustion Laboratory using valves to control the propellant flowrate. Turbine flow meters replace the critical venturis in an attempt to measure the flowrate. Several challenges arose during this experimentation with the data requiring to be processed to account for turbine flow meter time lag and adjustments for the characterization of the new throttling system. The non-linear response time of the turbine flow meters due to the signal conditioning system created uncertainty to the amount of propellant flowrate at any given point in time. The injector element with its well-established resistance characteristics from the single point case experiments was used to verify the flowrate through the injector. Due to the lack of mass flow verification during the testing, the mixture ratio unintentionally drifted higher during a test run. Also, when the LOX manifold was actuated from dual to solo operation, a pressure rise resulted that did not dampen in time to provide any useful data. Figure 13 presents a composite of data from fifteen tests of the LOX mass flow across the chamber pressure from 200 to 800 psia.
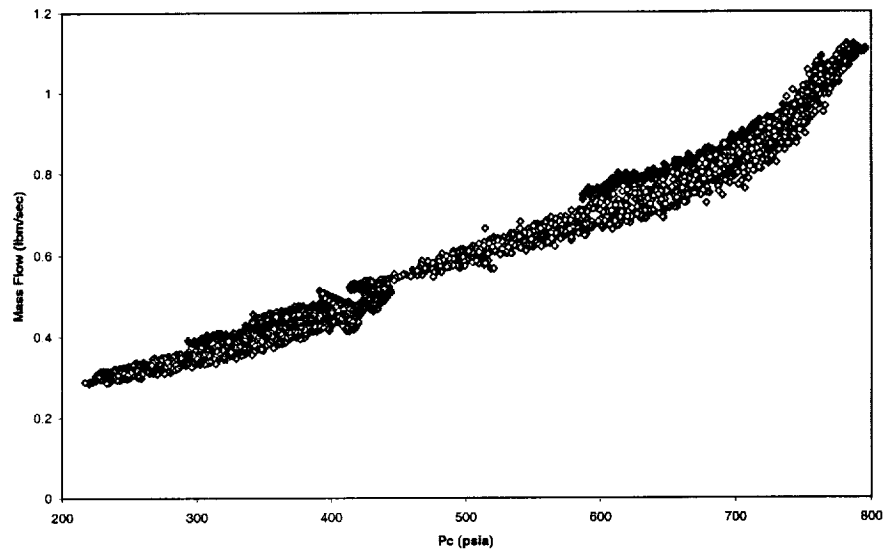

Figure 13: LOX mass flowrate data from fifteen throttling attempts with dual LOX manifold operation. Mixture ratio unintentionally increased from 6.0 to 7.0 through 8.2.

     Since the mixture ratios were higher than the target of 6.0, the inviscid swirl theory projection was adjusted for the higher LOX flow rates. Figure 14 is the characteristic throttling plot of $\Delta P/Pc$ versus Pc with the original projection for mixture ratio of 6.0 and the adjusted projection for the flowrates in Figure 13.
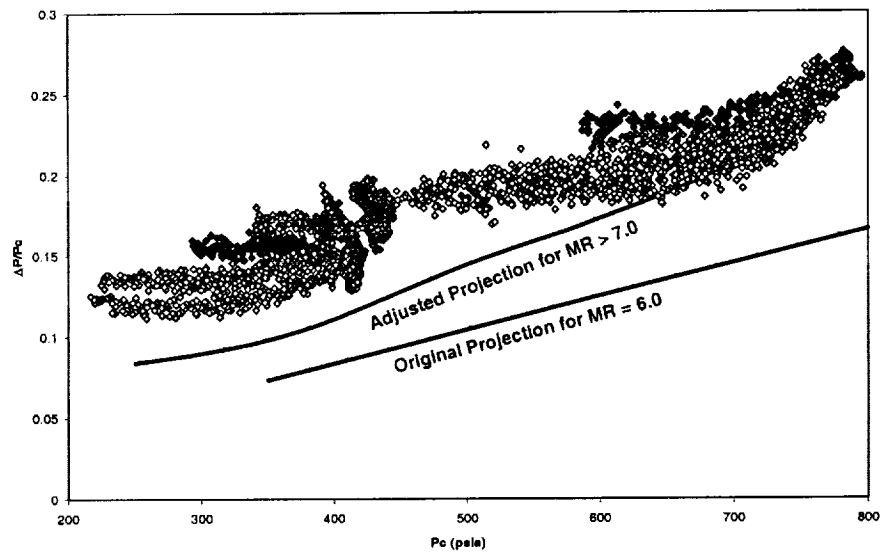
Figure 14: The inviscid swirl theory projection was adjusted for the higher LOX mass flowrates.

SUMMARY

A throttleable LOX/GH$_2$ swirl injector has been successfully designed to have a 10:1 throttleable range and demonstrated by steady state, single point cases and dynamic throttling experiments. Trends in performance showed nearly an optimum C* efficiency at the middle of the throttleable range utilizing the shear GH$_2$ injector plate with pressure drops slightly higher than the predicted with inviscid swirl theory. Switching to a co-swirling GH$_2$ injector plate appears to have improved atomization, mixing and consequently C* efficiency. Dynamic throttling was successfully attempted and the inviscid swirl theory projection was adjusted for the higher LOX mass flowrates. This demonstrated that this injector followed the model across at least the majority of the throttleable range.

ACKNOWLEDGEMENTS

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