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INJECTOR RESEARCH FOR SHUTTLE OMS UPGRADE USING LOX/ETHANOL PROPELLANTS

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Abstract

The combustion performance, heat transfer, and stability characteristics of bi-propellant swirl coaxial, and pintle injectors using LOX and ethanol propellants were investigated at representative thrust chamber conditions. The injectors were designed for sub-scale uni-element operation based on the target geometry and operating characteristics of an upgraded non-toxic orbital maneuvering system (OMS) engine. Several different versions of the Russian heritage swirl injector were tested. Combustion efficiency, injector face temperature, high frequency pressure, and shadowgraph spray imaging results are reported for hot-fire conditions. The results exhibit a wide range of C* efficiency values. Pulsed shadowgraph images reveal the effect of several flow phenomena, such as LOX flashing and spray self-pulsation, on combustion efficiency.

Nomenclature

Isp	specific impulse
C*	characteristic exhaust velocity
C_d	discharge coefficient
$\dot{m}$	mass flow rate
U	flow velocity
TMR	total momentum ratio
BF	blockage factor
D	nozzle diameter for swirl injector
d	tangential entry orifice diameter for swirl injector

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Introduction

NASA Johnson Space Center is investigating the feasibility of a non-toxic orbital maneuvering system (OMS) and reaction control system (RCS) upgrade for the Space Shuttle Orbiter. It is anticipated that this effort would result in cost savings, safety enhancements, reductions in operational complexity, and increased mission flexibility.[1] In addition, development of these non-toxic systems could prove valuable for future planetary missions such as the Human Exploration and Development of Space (HEDS) missions that use oxygen produced from in-situ planetary resources. Cost savings would be achieved through elimination of toxic propellant handling from the Orbiter processing flow, significant reduction in propellant cost, and relaxed leakage requirements. Safety and mission reliability can be improved by reducing the number of critical components. Additionally, mission flexibility could be enhanced by combining the OMS and RCS propellant storage and pressurization systems.

The current OMS engine was designed to operate with the hypergolic propellants nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH) at a chamber pressure of 125 psia and a nominal oxidizer to fuel mixture ratio of 1.65.[2] A vacuum thrust of 6000 lbf and a minimum Isp of 316 seconds are produced. The engine has an approximately 8 in. diameter injector face and combustion chamber. The nozzle expansion ratio is 55:1.

Design guidelines for the upgraded OMS engine were defined by NASA Johnson Space Center. For the upgraded engine, a LOX/ethanol propellant combination has been selected, and the propellant tank pressure has been increased to 350 psia, enabling an increase in chamber pressure. The engine is must produce thrust in the range of 3500 to 6000 lbf with a minimum specific impulse of 320 seconds. The upgraded OMS must fit into the same Shuttle Orbiter envelope as the current system.

Calculations indicate that for the LOX/ethanol combination, a total propellant mass flow rate of 18.4 lbm/s would provide an Isp of 326 seconds and a thrust of 6000 lbf at a mixture ratio of 1.70 and a chamber of 160 psia. The higher tank pressure of the upgraded OMS permits higher chamber pressure, which in turn allows a throat area reduction and greater nozzle expansion ratio in the same physical envelope. The individual propellant flow rates are11.6 lbm/s of LOX and 6.8 lbm/s of liquid ethanol. The following discussion on design conditions for uni-element operation are based on these numbers.

Successful development of an adequate thrust chamber will be a key element in the achievement of an upgraded OMS using non-toxic propellants. This paper will focus on the measurement of detailed combustion characteristics of liquid oxygen/ethanol propellants at representative conditions for candidate injector configurations. Measurements of propellant spray field, combustion profile, characteristic exhaust velocity (C*) efficiency, and heat flux to the injector face are being conducted for each injector configuration.

Injector Designs

Background

In this study, three types of injector elements, the bi-propellant (or bi-centrifugal) swirl coaxial, pintle, and impinging jet injector, have been designed and are being investigated for possible OMS applications. An impinging jet injector is used in the existing OMS. There exists in the U.S. a substantial experience base for this injector type. The bi-propellant swirl and pintle injectors have potential advantages over the impinger in terms of cost and operability. These injectors both operate at a higher thrust/element than the impinging jet injector, which can reduce cost. Furthermore, these injector types potentially operate over a wider range of conditions, thereby allowing deeper throttling and use of multiple fuels, a significant advantage for HEDS applications.[3] (Although variable thrust operation is not an OMS requirement, NASA would like to leverage this development work for application to HEDS where throttling is a key requirement.)

The bi-centrifugal swirl coaxial injector element is being investigated for the OMS upgrade because of its good mixing/combustion characteristics and its potential for deep throttling. Historically, this injector has never been utilized in the U. S. (It has some similarities to the gas/liquid swirl coaxial injector used occasionally in the U.S.) This injector has proven its efficiency and reliability over 50 years of usage in different types of Russian liquid propellant rocket engines (LRE) ranging from open cycle LREs with low and medium thrust for Earth and space missions, and in closed cycle LREs where they are widely used in gas generators.

The bi-propellant swirl injector element was chosen as the baseline to set nominal propellant flow conditions for the experiments. The element arrangement shown in Fig. 1 was deemed to be the baseline arrangement for a full-scale multi-element OMS bi-centrifugal injector. This arrangement with four circular rows uses 60 elements. Alternate arrangements with three or five rows would have 36 or 90 elements, respectively. The three-row arrangement would be cheaper to manufacture but has an associated lower level of atomization efficiency. The five-row arrangement would be more attractive in terms of atomization efficiency but would be costlier to manufacture. The four-row arrangement was chosen based on Russian experience as a reasonable compromise between atomization efficiency and complexity.

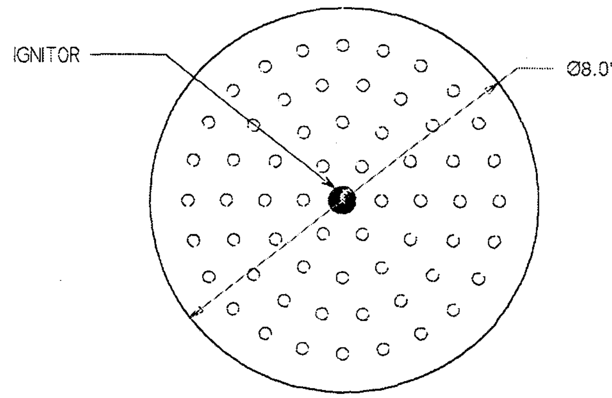


Fig. 1. Element layout arrangement chosen for OMS engine injector face with swirl elements.

With the known total mass flow rate and the baseline injector element configuration defined, the required mass flow rate per injector element is thus 0.307 lbm/s, i.e., 1/60 scale. This mass flow rate at a chamber pressure of 160 psia was designated the baseline flow condition for experimentation at which all injector configurations would be compared.

The pintle injector is typically designed as a single element injector for any size chamber. However, the flow requirements for the OMS engine are well beyond the capabilities of the laboratory at Penn State. Consequently, the following two options were available: to investigate a sub-scale injector element, or investigate a sector of a full-scale injector. The decision was made to investigate a sub-scale injector designed for optimum performance at the flow rate conditions defined for the bi-centrifugal swirl element. Note that scaling arguments will be necessary to extrapolate the results obtained for this experimental pintle injector to full-scaleOMS flow rate conditions.

The impinging jet injectors to be used as part of this study are being designed and fabricated by Aerojet. One will have the actual elements that Aerojet envisions for the upgraded OMS engine and the other will be a like-on-like doublet impinger similar to the currrent OMS engine injector design. Note that thanks to the implementation of platelet technology, Aerojet's injector elements are typically smaller than conventional injector elements. Consequently, to form a basis for comparison with the other injector elements, the Aerojet design will incorporate multi-elements such that the total propellant flow rate is the same as that of a uni-element bi-centrifugal swirl coaxial injector. Unfortunately the impinging jet injectors were not available in time for inclusion in this paper. Results for these injectors at the flow conditions outlined above will be included in a future publication.

Design Characteristics

Bi-Centrifugal Swirl Coaxial Injector. A classic swirl injector consists of an axisymmetric vortex chamber and nozzle that are supplied by a pressurized liquid through multiple tangential channels. As the liquid enters through the tangential channels, it rotates in the vortex chamber, forming a freeinterior surface, the diameter of which increases as the vortex chamber diameter contracts. Thus, the exit nozzle provides an increase in axial velocity. The liquid film leaves the nozzle exit as a thin axisymmetric hyperbolic sheet. The bi-centrifugal swirl injector is essentially one swirl injector inside of another one and designed in such a way that the final spray is a single combined cone comprised of the two liquids.

The bi-centrifugal swirler was designed based on the theory of wave propagation along the liquid swirled flow interior surface.[3] The theory, based on ideal liquid assumptions, relates the mass flow rate, spray output velocity, liquid film thickness in the vortex chamber and nozzle, and spray angle to the key injector element sizes: diameters of the nozzle (D), vortex chamber, and tangential channel orifice diameter (d). Identical vortex chamber diameters were used for all the elements considered in this study.

The baseline designs of the bi-centrifugal swirl injector element corresponding to the flow rate requirements described previously is shown schematically in Fig. 2 and are denoted as elements "2" and "2M". In this design, ethanol enters the inner swirl element through the tangential channels at section B-B and LOX enters the outer vortex chamber through the channels at section A-A. Several permutations of this basic design were tested in this study. The key differences in the dimensions of the several injector designs are noted in Fig. 2. The 1M, Δ2, and 2O injector elements all use LOX on the outside. The Δ3A and the 3B were designed to use a reversed propellant scheme with LOX on the inside and ethanol on the outside. The Δ configurations use a narrowed conical gap between the swirl chambers as noted in Fig. 2. The gap size for the baseline configuration is 0.071 in. The logic for creating these alterations to the basic design is described in the Results and Discussion section.

The bi-propellant swirl injector manifold assembly is shown in Fig. 3 wit h (1) being the injector faceplate, made from oxygen-free copper, and (2) being the swirl element itself. Note that having LOX as the outer swirled propellant provides substantial cooling for the faceplate. Another design permutation explored was replacing the faceplate shown in Fig. 3 with another depicted in Fig. 4 that had a considerable extension, recessing the swirl element by 1 in. This provided a confined propellant mixing and pre-combustion chamber that exhibited large influence on global performance. This large recess was used with the 2M, 2O, and Δ3A elements.

Pintle Injector. The pintle injector design for this study is based on earlier work at Penn State University involving a LOX/RP-1 pintle injector.[4] The design features of the pintle are shown in Fig. 5. As the schematic illustrates, the injector is comprised of a post located in the center of an annulus. One propellant, either the fuel or the oxidizer, flows through the central post turning 90 degrees to flow radially through the slots at the tip of the post. The other propellant flows axially through the annulus, then mixes with the spray emanating from the slots, and forms a hollow spray cone. For the current project, a fuel-centered configuration was selected based on geometric requirements and previous Penn State experience.

One of the key design parameters is the total momentum ratio (TMR), which is defined as follows:

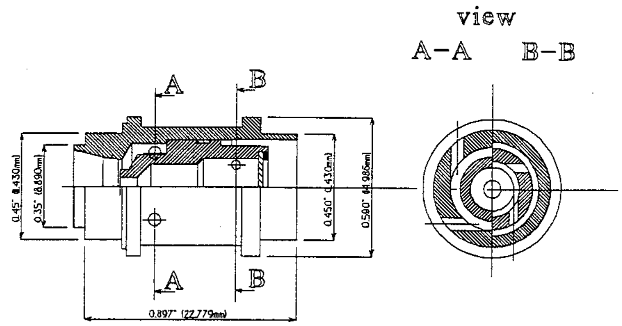
$$TMR = \frac{(\dot{m} * U)_{InnerFlow}}{(\dot{m} * U)_{OuterFlow}} \quad (1)$$

TRW's experience with LOX and RP-1 at NASA Lewis indicated that at a momentum ratio near unity, the highest performance resulted.[4] This experience was followed for the present design.

Another important parameter is the blockage factor (BF) defined as:

$$BF = \frac{\sum SlotWidths}{TubePerimeter} \quad (2)$$

A blockage factor of unity indicates that mixing is caused totally by collisions. As the blockage factor is reduced, collisional mixing decreases and is enhanced by interfacial (shear) mixing. TRW's experience has been with blockage factors between 0.3 and 0.7.[4] As was confirmed in cold flow testing, the spray angle



2

D_{inner} = 0.090"
D_{outer} = 0.236"

d_{inner} = 0.055"
d_{outer} = 0.063"

2M

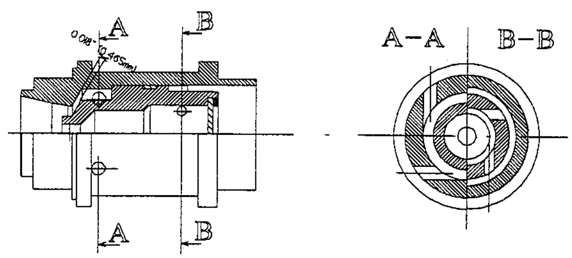
D_{inner} = 0.110"
D_{outer} = 0.236"

d_{inner} = 0.060"
d_{outer} = 0.063"

1M

D_{inner} = 0.110"
D_{outer} = 0.226"

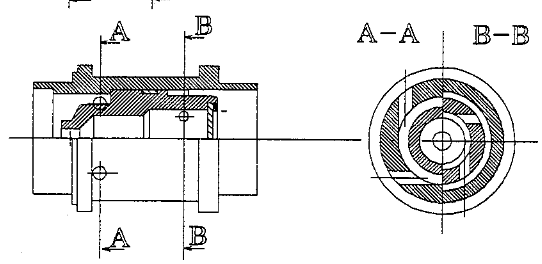
d_{inner} = 0.039"
d_{outer} = 0.050"



Δ2

D_{inner} = 0.100"
D_{outer} = 0.236"

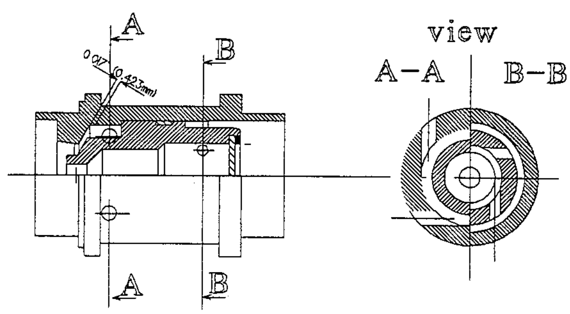
d_{inner} = 0.055"
d_{outer} = 0.063"



2O

D_{inner} = 0.110"
D_{outer} = 0.362"

d_{inner} = 0.055"
d_{outer} = 0.040"

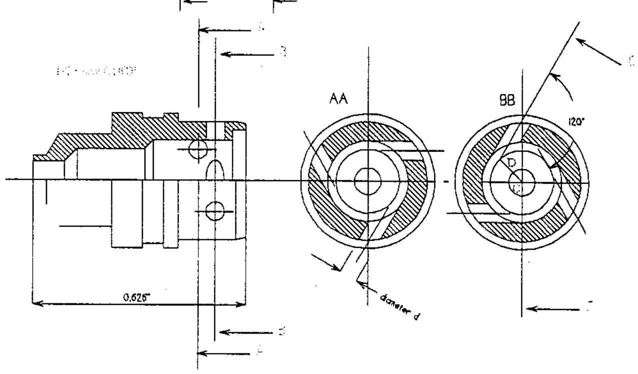


Δ3A

D_{inner} = 0.110"
D_{outer} = 0.236"

d_{inner} = 0.055"

d_{outer} = 0.049"



3B (interior part, exterior same as Δ3A)

D_{inner} = 0.110"
D_{outer} = 0.236"

d_{inner} = 0.068"
d_{outer} = 0.045"

Fig. 2. Bi-propellant swirl injector element design variations.

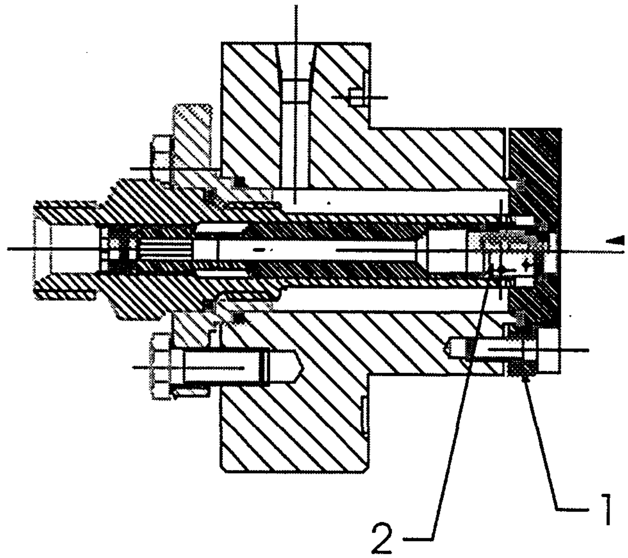


Fig. 3. Swirl injector manifold assembly.

is strongly dependent upon both the total momentum ratio and the blockage factor.

The final design specifications of the K1 and D3 pintle injectors are shown in Table 1. K1 denotes the LOX/ethanol injector designed specifically for the OMS condition. The D3 injector was designed for use with LOX/RP-1 propellants, operating at different mass flow rates and chamber pressures. However, it was tested using the OMS operating conditions to examine pintle performance during off-design conditions.

A drawing of the K1 pintle injector post is shown in Fig. 6. Note that the internal cusp shape of the plug is instrumental in redistributing the fuel radially through the slots. Also, a smooth contoured injector face, as shown shaded in Fig. 7, is utilized during combustion tests. The shape of this injector face is elliptical in plan view and symmetrical about the chamber centerline. It is compatible with the circular cross section combustion chamber and promotes recirculation zones that are critical to the pintle's performance and cooling of the chamber face.

Table 1. Pintle Injector Design Characteristics.

	K1 Pintle Injector	D3 Pintle Injector
LOX flow rate (lbm/s)	0.193	0.74
Fuel flow rate (lbm/s)	0.114	0.27
Design O/F	1.7	2.7
Design P_c (psia)	160	354
Propellant orientation	Fuel-centered	Fuel-centered
Pintle post D_i (in.)	0.135	0.210
Pintle post D_o (in.)	0.165	0.250
Annulus D_i (in.)	0.194	0.330
Number of slots on pintle tip	12	24
Dimension of slots on pintle tip (in. x in.)	0.026x0.013	0.02x0.01
Pintle flow (fuel) C_d	0.63	0.64
Annular flow (LOX) C_d	0.55	0.80
Pintle flow (fuel) pressure drop (psid)	90	44
Annular flow (LOX) pressure drop (psid)	66	321
TMR	1.02	1.25
BF	0.61	0.60

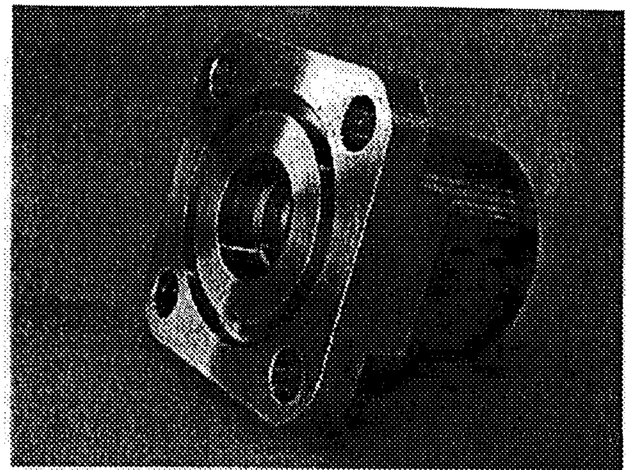


Fig. 4. Large recess faceplate for swirl injector element.

Experimental Setup and Conditions

Test Facility

The experiments were conducted at the Cryogenic Combustion Laboratory located at The Pennsylvania State University. This laboratory provides the capability of firing both gaseous and liquid propellant uni-element rocket injectors at realistic flow rates.

The injector characterization experiments are being conducted using two different optically accessible rocket chambers. A chamber with a 2 in. circular cross section is used for the pintle tests as shown in Fig. 7. The chamber is modular in design allowing rearrangement of the sections or the length to be changed easily. It has optical access and ports for heat flux gages and high frequency pressure transducers. The chamber used for the swirl injector tests is similar in design to that used for the pintle experiments except that the internal cross-section is 2 in. square. The swirl injector manifold assembly shown in Fig. 3 is located on the square cross-section chamber in similar manner to the pintle manifold assembly on the round chamber.

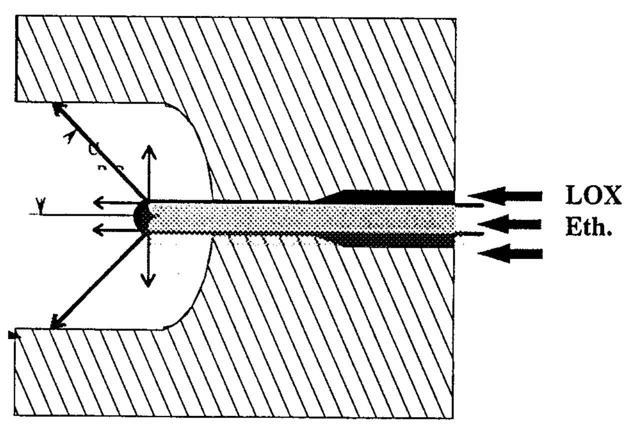


Fig. 5. Schematic diagram of pintle injector.

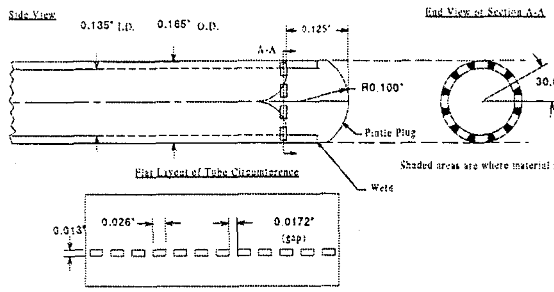


Fig. 6. K1 pintle post and plug assembly.

The windowed section used for the swirl injector experiments has four 2 in. diameter windows on opposing sides. Since the pintle chamber has a circular cross-section, the windows are smaller (1.25 in. diameter) to minimize flow field disturbance. Two of the windows in the pintle chamber are 150° apart for use in drop-sizing experiments, and a third window is 90° from one of the other windows for imaging diagnostics.

Both rocket chambers are oxygen-free copper heat-sink designs. The time duration of firings in this study was limited to 4-5 seconds to prevent window and chamber overheating.

The test matrix used to characterize the OMS candidate injectors consists of six cases as shown in Table 2. Case 2 corresponds to the upgraded LOX/ethanol OMS engine (1/60 scale) condition as defined earlier. Mixture ratio variation effects using target values of 1.4 and 2.0 are investigated for the OMS operating pressure as well as at an elevated pressure of 300 psia. For the higher pressure cases, the propellant flow rates are increased to obtain the greater chamber pressure without changing the nozzle diameter. Thus Cases 4-6 represent throttled up (~2:1) conditions for the OMS candidate injectors.

Experimental Measurements

Several conventional combustion measurements have been made, including relative C* efficiency, injector face temperature, wall heat flux, injector pressure drop, and time-accurate pressure history. A thermocouple is imbedded just beneath the injector faceplate surface to characterize face heating for different injector configurations.

Optical diagnostic measurements have been made in the form of line-of-sight CH-radical emission to map the combustion profile, shadowgraph imaging to capture the liquid spray profile, and combustion light videography. The CH emission images are a 1 microsecond exposure taken through a 430nm narrow bandpass filter in front of an intensified CCD camera. The shadowgraph images are lit by a high power, ~20 ns xenon flash (~500kW peak power) within a 200 ns gated intensifier exposure that successfully eliminates all combustion light. With both these techniques, only one image is captured per run.

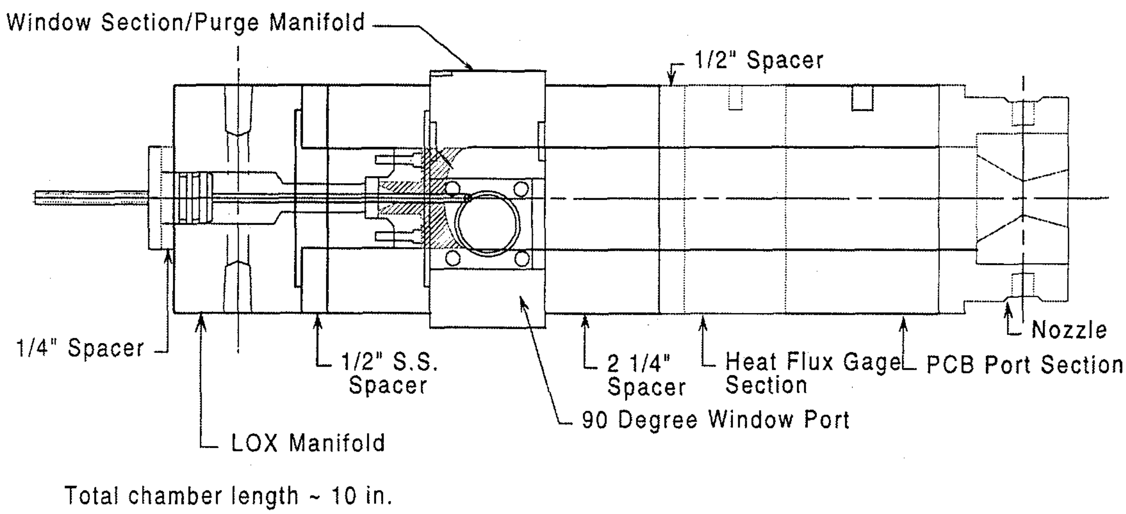


Fig. 7. Sub-scale rocket for pintle tests.

Table 2. Test Matrix.

Case #	1	2	3	4	5	6
Pc (psia)	160	160	160	300	300	300
O/F	2.0	1.7	1.4	2.0	1.7	1.4
LOX flowrate (lbm/s)	0.210	0.193	0.180	0.391	0.361	0.341
ethanol flowrate (lbm/s)	0.105	0.114	0.129	0.195	0.212	0.244
GN2 flowrate (lbm/s)	0.030	0.030	0.030	0.030	0.030	0.030
Nozzle Dia (in.)	0.650	0.650	0.650	0.650	0.650	0.650

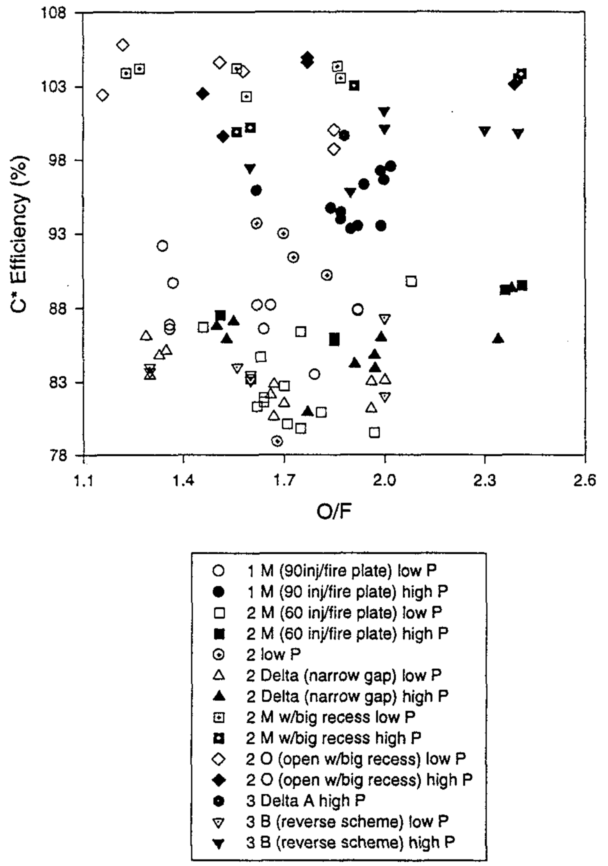


Fig. 8. C* Efficiency vs. O/F for several bi-centrifugal swirl coaxial injectors

Combustion light videography is done with an un-intensified CCD camera shuttered for a 0.1 ms exposure. With this technique one can easily obtain 20 or more images per run. Only the shadowgraph images of the instantaneous liquid spray field will be reported in this paper.

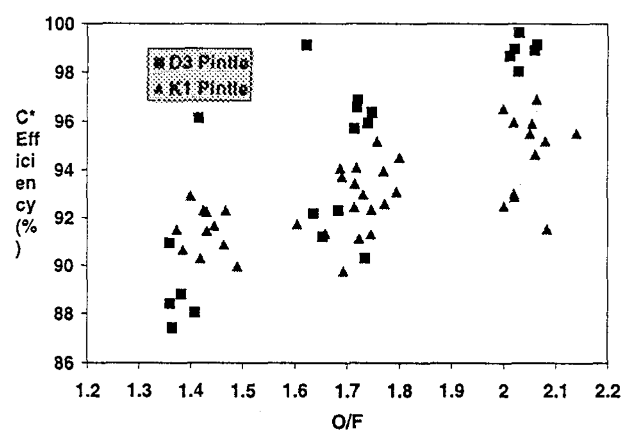


Fig. 9. C* Efficiency vs. O/F for the K1 and D3 pintle injectors.

Results and Discussion

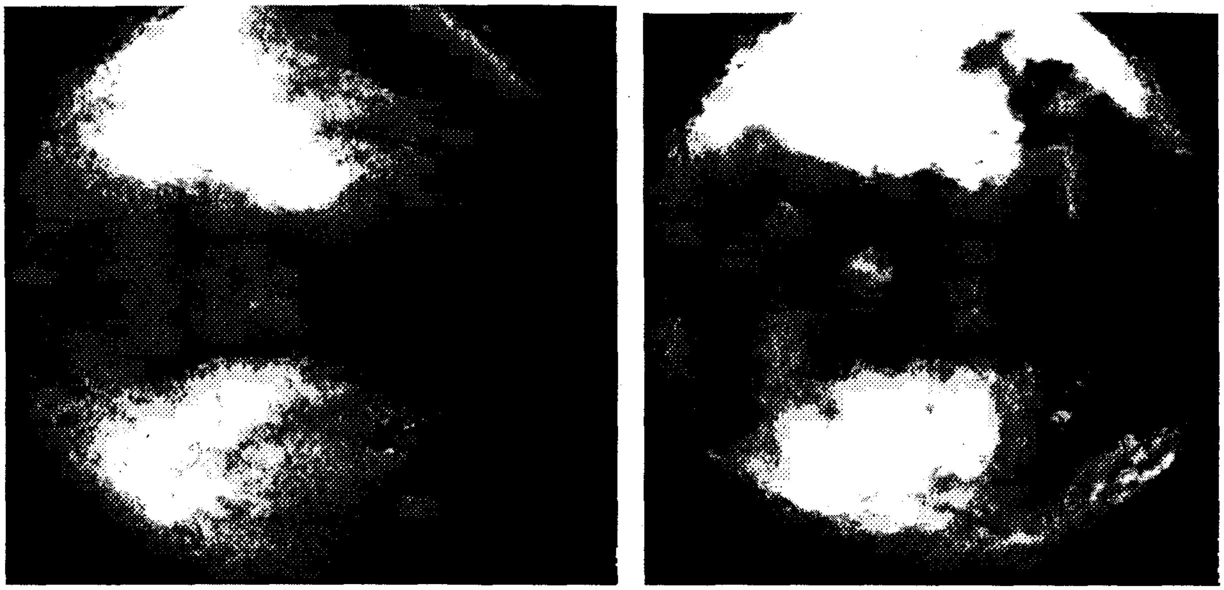
Over 200 LOX/ethanol hot-fire experiments have been conducted for the various versions of the bi-propellant swirl injector and the pintle injector. A majority of the experiments are represented in Fig. 8 for the swirl injector and Fig. 9 for the pintle in terms of C* efficiency versus mixture ratio. These results include both the lower chamber pressure cases (1-3), closest to the OMS operating condition, and the higher pressure cases (4-6) (swirl injectors only) corresponding to a throttled up condition. A wide range in performance was recorded for the various configurations and experimental conditions. The following discussion will attempt to address the recorded performance and relate it to relevant features of the injector designs and corresponding spray phenomenology.

C* efficiencies were calculated from the experiments sometimes above 100%. This, of course, is unrealistic. The authors have yet made no attempt to correct the C* efficiency numbers for non-equilibrium conditions, unsteadiness in flow or gas properties, heat transfer, wall erosion, or nozzle non-idealities. The uncorrected values; however, should offer good relative accuracy for comparing firings at similar conditions as was the intent in this study. The gaseous nitrogen window curtain flow, which was typically 5-10% of the total propellant flow was accounted for in the theoretical evaluation of chamber pressure as if it were fully mixed into the flow field.

Swirl Injector. Initial experiments for the bi-centrifugal swirl injector were conducted with the 1M and 2M injector elements. These two similar injector designs were based on Russian experience with earth storable, hypergolic propellant injectors, in which the swirling propellant spray cones are formed with divergent angles at the exit of the respective vortex chamber nozzles and then forced to coalesce into a single mixed cone by hydrodynamic forces in the contoured exit nozzle of the element.[5] This study represents the first time that a cryogenic propellant was used with this particular design. Using the short-pulse shadowgraph technique to visualize the spray field, it was discovered that the LOX and ethanol spray cones would not coalesce and mix as intended in the nozzle.

Shadowgraph imaging revealed that under hot-fire conditions, the ethanol cone angle was about 25-30°, while the LOX cone angle was typically 70-90° and even as much as 120°. This was in contrast to cold flow (water) test results in which both swirled sprays mixed inside the profiled exit nozzle to form a combined spray cone of about 60-74°.

This unexpected propellant separation was presumably due to the low pressure operating condition of interest here in conjunction with the relatively high



(a) (b)

Fig. 10. Shadowgraph imaging reveals LOX and ethanol spray cone separation. (a) 2M injector , case 2 (b) 2M injector, case 6.

vapor pressure liquid oxygen available at the Cryogenic Combustion Lab such that oxygen was near or beyond the equilibrium flash point at the injector/chamber conditions. Thus the quality of LOX in the injector element and chamber was suspect for these conditions. Since the swirl injector was designed for mixing two liquid flows, performance when the oxygen flow was in two phases was not as high as anticipated. Images of the resultant spray pattern, as seen in Fig. 10, suggest that the outer LOX flow is separated from the ethanol spray cone by a layer of vaporized oxygen. Since the oxygen is swirling, the liquid is centrifugally separated from the gaseous oxygen. As the gaseous O_2 expands, it forces the two liquid flows away from each other, narrowing the ethanol cone and expanding the LOX cone.

The performance issue with regard to LOX quality is addressed in Fig. 11 where C* efficiency is plotted versus chamber pressure divided by the vapor pressure of the oxygen at the injector inlet conditions. Note that abscissa values greater than unity reflect reasonable LOX quality within the injector and upon issuing into the chamber and values below unity indicate questionable or uncertain LOX quality throughout the injector. In the latter case, it is possible that flashing is occurring locally inside the injector and likely upon issuing into the chamber. The general trend with respect to the LOX quality parameter is that C* efficiency increases with improving LOX quality margin for the 2M and 1M (as well as the 3B) bi-centrifugal swirl injectors.

The experiments with the 1M injector element, which was sized for a five-row, 90-element full-scale injector, were conducted at the 1/60 OMS scale propellant flow rate of Case 2. Thus, this injector exhibited considerably higher pressure drop, especially on the ethanol side, compared to the 2M injector at the same conditions. See Table 3 for relative magnitudes of pressure drop for Cases 2 and 5 for the swirl injectors. This resulted in comparatively higher performance, 93% - 98% C* efficiency for the higher pressure cases but at the expense of unreasonably high ΔP. These extremely high pressure drops may lead to operation in unstable combustion regimes as well. Experiments with the 1M injector can be regarded as an

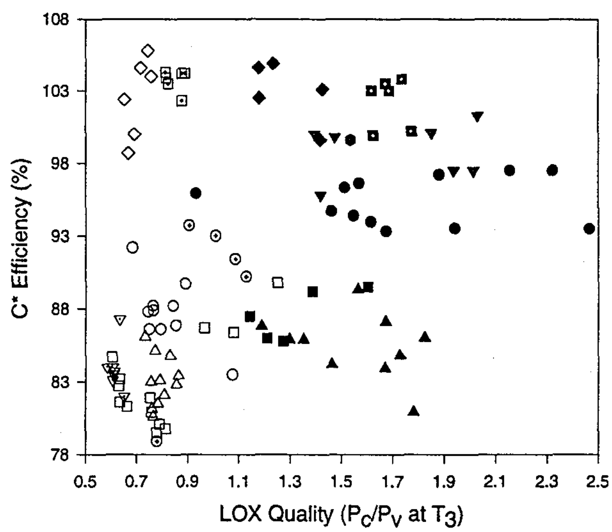


Fig. 11. C* Efficiency vs. LOX quality for several bi-centrifugal swirl coaxial injectors. Same legend as in Fig. 8.

Table 3. Nominal Pressure Drop Characteristics Of Bi-Propellant Swirl Injectors.

Swirl Injector		1M	2M	2M+	2	Δ2	2O+	3B	Δ3A+
Case 2	ΔP_{LOX}	90	65	100	60	65	130	125	—
	ΔP_{ETH}	145	45	85	60	65	125	95	—
Case 5	ΔP_{LOX}	300	225	260	—	225	—	410	490
	ΔP_{ETH}	475	180	275	—	250	—	380	475
ΔP in psid; + means with faceplate with 1" recess ; — indicates that case was not tested									

example of an OMS scale injector throttled up more than twice from its design thrust level.

Considering the 1M and 2M injectors, several design options were explored to address the performance decrement from marginal LOX quality causing inhibited propellant mixing. The injectors that represent these design modifications are the Δ2 and the 3B, as well as the use of an injector faceplate that provided a 1 in. long, 0.45 in. diameter recess of the injector element. The large recess was fired with the 2M, 2O, and Δ3A elements.

The Δ2 injector is very similar to the 2 and 2M injector elements except that as shown in Fig. 2 it has a narrowed annular, conical gap between the outer (LOX) and inner (ethanol) swirl chamber nozzles that serves to increase the axial LOX velocity and reduce the spray exit angle. It was discovered in cold flow experiments that by controlling the size of this gap one could vary the outer swirl spray angle in the range of about 12°-25° without altering the mass flow rate. The intent in reducing the LOX cone angle was an attempt to force the LOX and ethanol spray cones to directly impinge, hopefully overcoming the separation forces created by the expanding gaseous oxygen component. However, as can be seen in Fig. 12, the spray cones were still forced apart, perhaps even more vigorously with the increased axial velocity of any gaseous oxygen bubbles from the narrowed channel. From the typical image in Fig. 12, it appears that LOX does not survive as liquid very far into the chamber, and thus is not available to help breakup and readily mix with the ethanol cone as designed. Accordingly, the C* efficiency for the Δ2 injector was always lower than about 90% with a majority between 83 and 88%. Interestingly, the combustion efficiency for the Δ2 injector seems somewhat insensitive to the LOX quality parameter. The higher pressure cases with greater LOX temperature margin exhibit similar C* efficiency values to the lower pressure cases, and the spray cones were likewise separated. In summary, the Δ2 injector did not behave as intended since the gas dynamic forces could not be overcome.

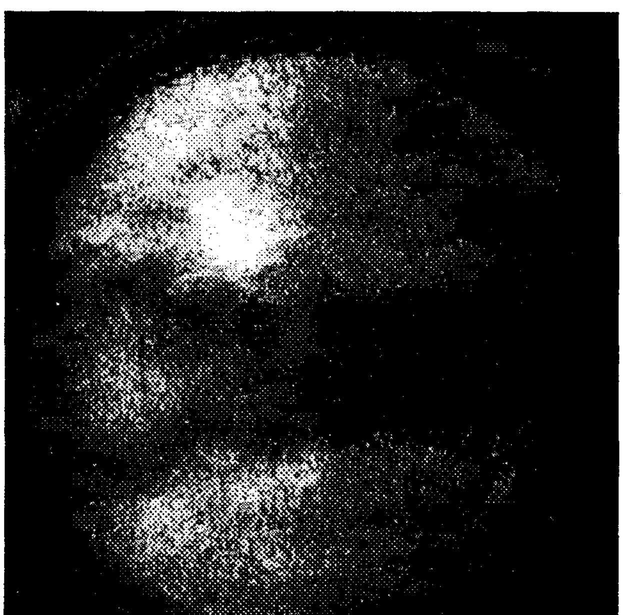


Fig. 12. Δ2 bi-centrifugal swirl coaxial injector design for narrow LOX cone angle still exhibits propellant separation.

Since the presumably two-phase oxygen at these low chamber pressures was determined to separate and force the liquid to a larger than designed angle, it was decided to create an injector that might use this effect to advantage. Thus, the 3B bi-propellant swirl injector, with key dimensions as indicated in Fig. 2, was designed to operate with LOX as the inner fluid and ethanol as the outer fluid. The idea being that if the LOX was going to be centrifugally forced outward, then let the fuel be on the outside to mix with the LOX. C* efficiency results for this so-called "reverse scheme" injector are shown in Fig. 11. Shadowgraph imaging results show that this scheme worked well for the higher pressure cases. In Fig. 13, the flow field exiting the injector appears to be a well mixed bi-propellant liquid flow, and the C* efficiency measurements are in the neighborhood of 100%. The same is not true for the lower pressure cases, where mediocre C* efficiencies in the range of 80-88% were recorded. Shadowgraph imaging for these cases did not reveal much information about the flow field, perhaps due to the ethanol cone expanding to and coating the windows. Very poor LOX quality in these lower pressure cases may have resulted in poor mixing, i.e., there may have been no substantial LOX cone to conduct direct mixing with the ethanol cone.

The other injector design option that was explored to provide good mixing and performance over a range

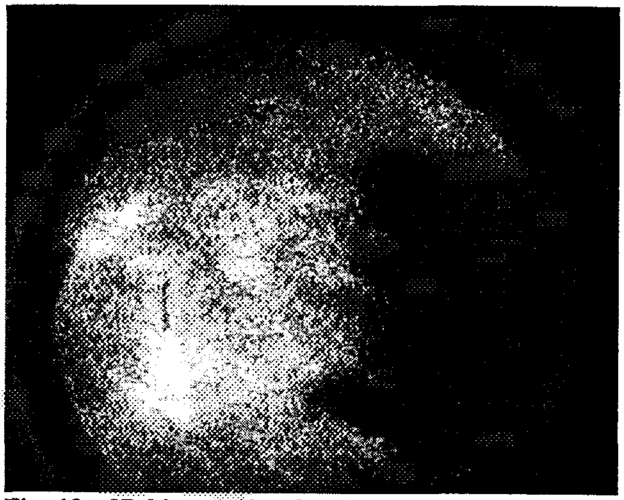


Fig. 13. 3B bi-centrifugal swirl coaxial injector with ethanol on the outside (reverse scheme) exhibits good mixing and performance for high pressure cases.

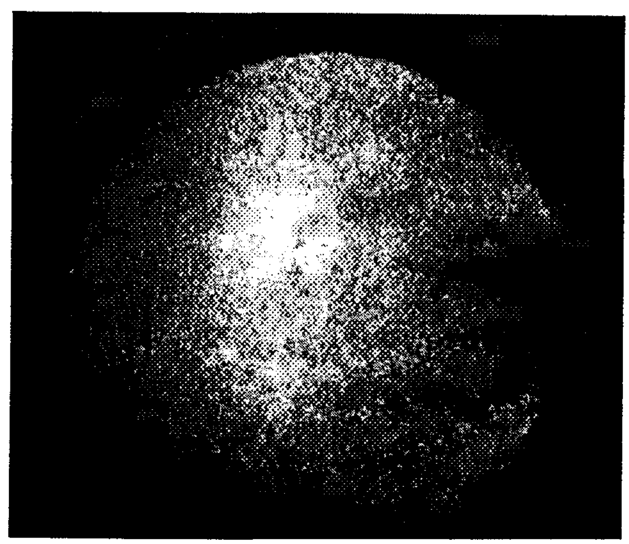
of conditions with marginal LOX quality was the use of a large recess for the injector element to provide a confined space to force propellant mixing. A faceplate was designed with a 1 in. recess for the swirl injector, offering a mixing chamber of that length and 0.45 in. diameter. This experimental faceplate was designed conservatively long to see a large effect, with the idea that one would optimize its length for good performance with minimal added ΔP and minimal risk of overheating the extended face. The large recess worked well for enhancing performance for all cases of each element that was used with it. The highest C* efficiencies were achieved with this concept, the minimum being greater than 98%. The large recess was used with the 2M, 2O, and Δ3A injectors. The 2O and Δ3A were designed specifically to be used with the large recess. The additional pressure drop penalty of using the large recess is illustrated in Table 3. Note that the combustion efficiency while using the large recess is insensitive to LOX quality.

The 2O is a LOX outside, ethanol inside bi-centrifugal swirl injector, as seen in Fig. 2, with no nozzle on the LOX swirler. The absence of a nozzle minimizes the axial velocity in favor of the tangential velocity so that residence time is maximized in the mixing chamber. Note that one would not use the 2O injector without a substantial recess since there is no flow resistance protecting the oxidizer circuit in the injector from disturbances.

Fig. 14 reveals the spray field for both low and high pressure cases for the 2M injector with the 1 in. recess. The surviving liquid emanates as a jet but is apparently consumed before the end of the window. Thus, the mixing chamber is very effective, but Fig. 14 suggests that radial striations may still exist in the flow field at the exit plane, especially for the lower pressure cases. The imaging results for the 2O injector were very similar to those for the 2M injector with the large recess.

The Δ3A is a reverse scheme (fuel outside) swirl injector element with a narrowed gap compared to the 3B. The narrowed gap was used to provide a reduced ethanol cone angle and increase the axial velocity in order to prevent overheating of the large recess since high performance was already achieved for the high pressure cases with the 3B injector. It was anticipated that significant combustion could occur within the long cavity, especially with the ethanol on the outside. While no significant damage to the recess or injector elements was incurred during firings with the 2M or 2O injectors, a single firing rendered the Δ3A unusable due to

(a)



(b)

Fig. 14. 2M bi-centrifugal swirl coaxial injector with large recess face plate exhibits good mixing and combustion over a wide operating range and insensitivity to LOX quality. (a) case 3 (b) case 4.

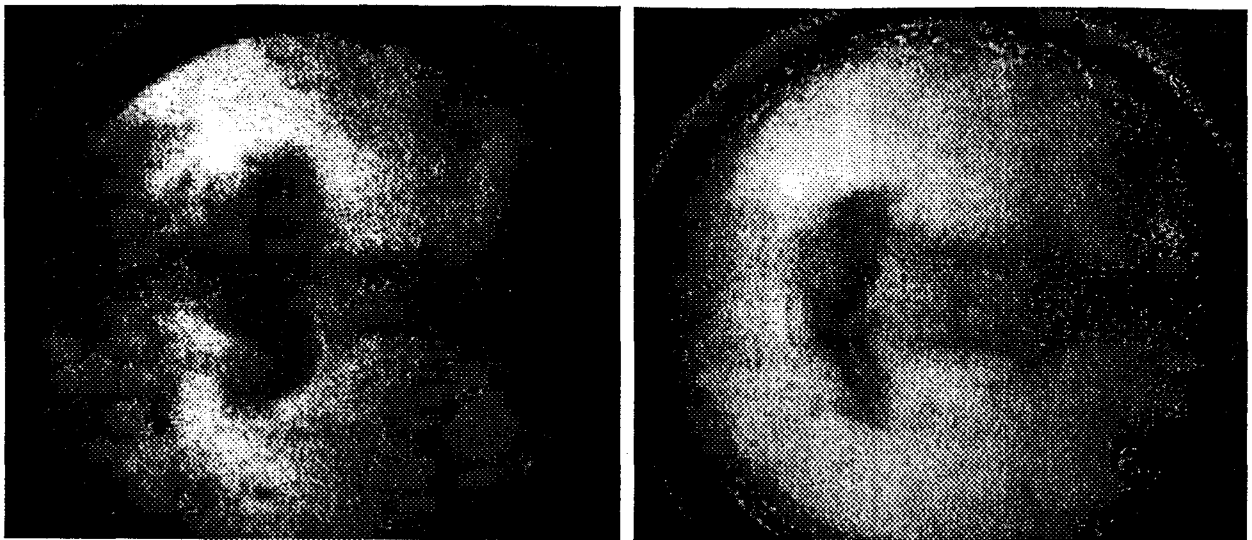


Fig. 15. Self-pulsations of the bi-centrifugal swirl spray field were discovered under certain conditions. Images shown for case 2 with number 2 swirl injector.

substantial burning of the end of the stainless steel injector element. In that lone firing of this element, shadowgraph imaging indicated that apparently no liquid survived to the end of the mixing chamber.

Another interesting phenomenon that was discovered to have a large effect on C* efficiency was hydrodynamic self-pulsation of the spray. This phenomena for this type of injector was first described by Bazarov[6] but was visualized in this study under realistic combusting conditions possibly for the first time. This hydrodynamic instability is primarily associated with coaxial gas/liquid flows. In the present case, the instability occurs due to the compressible gaseous or two-phase oxygen flow over the recessed central swirler liquid ethanol flow. Bazarov[6] found that the mean median drop size may be decreased by more than a factor of two during self-pulsations, compared to steady conditions. Hence this would explain the higher performance recorded in this study corresponding to these conditions. Figure 15 is an image captured of a 2 injector firing exhibiting strong self-pulsation characterized by the formation of large scale coherent structures. Such an image was common over a range of conditions for this and to a lesser extent the Δ2 injector. Note from Table 2 that injector 2 has 33% higher ethanol ΔP than the 2M. The 1M injector experiments exhibited self-pulsations for the higher pressure cases but at a frequency approximately two times higher. Self-pulsations of the spray do not necessarily translate to combustion instability, but do offer the opportunity for feedback at high frequency with chamber acoustics to exacerbate stability problems. Russian experience has identified the important design parameters, and they have been able to avoid operation of injectors in self-pulsation regimes.

Pintle Injector. A plot of C* efficiency vs. O/F for the pintle injectors is shown in Fig. 9. As O/F increases, C* efficiency generally increases for both the K1 and D3 injectors. For the K1 injector, the efficiency values near a given O/F were fairly consistent. This was true for the D3 injector only near an O/F of 2.05. The C* efficiencies recorded for the PSU pintle injectors are similar to those recorded by NASA and TRW for much larger scale engines using LOX and RP-1.[7]

Considering the issues of LOX quality experienced for the swirl injector, a plot of C* efficiency versus the LOX quality parameter is offered in Fig. 16. Note that all the hot fire tests for the pintle injectors were done at the low chamber pressure (160 psia). For the K1 injector, there appears to be a general trend that as the LOX quality increases, C* efficiency increases. However, the D3 injector performance seems to be unaffected by LOX quality.

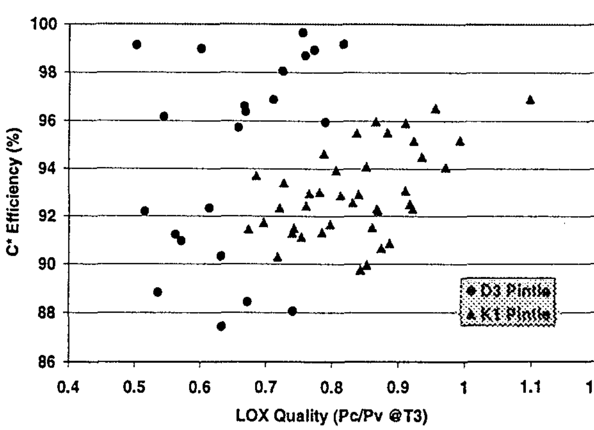
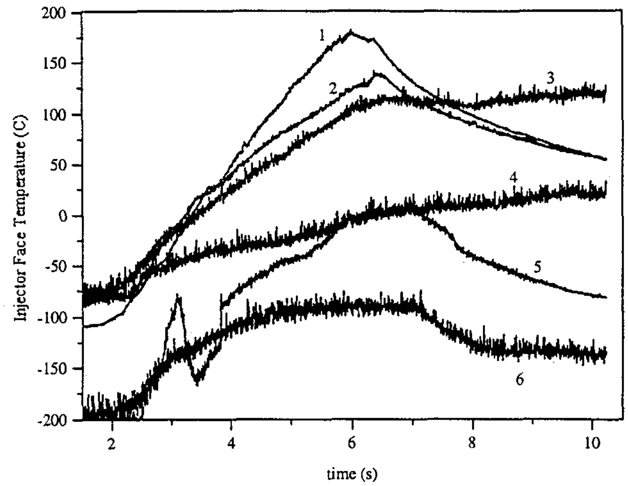


Fig. 16. C* Efficiency vs. LOX quality for the K1 and D3 pintle injectors.



Curve: 1 – D3 pintle Case 1, C*=91%
2 – K1 pintle Case 2, C*=94%
3 – 3B Case 4, C*=100%
4 – 3B Case 2, C*=84%
5 – 2M w/big recess Case 4, C*=102%
6 - 1M Case 4, C*=94%

Fig. 17. Example of injector face temperature vs. time traces.

Face Temperature

Typical plots of injector face temperature vs. time are shown in Fig. 17 for a variety of swirl and pintle injectors. The injector face temperatures stayed below 350 F in all cases but a steady state condition was not reached in most cases. Face temperatures started out very low due to heavy chilling of the injector/manifold to maximize LOX quality. The bi-propellant swirl injectors with LOX on the outside exhibited lowest face temperature thanks to the proximity of LOX to the face. The 1M injector example in Fig. 17 seems to have reached a steady condition at a temperature of about –210°F (100°C). As expected, highest swirl injector face

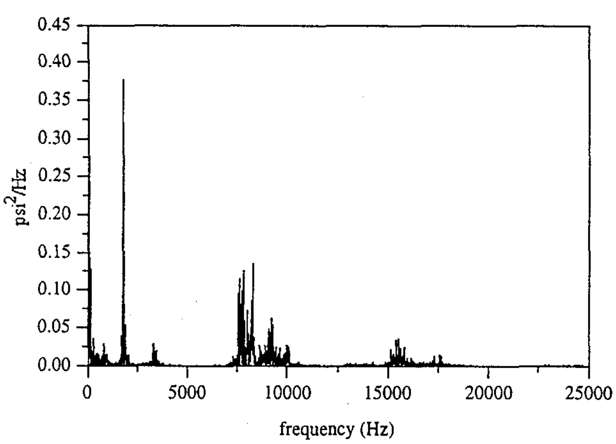


Fig. 18. Example power spectral density plot of chamber pressure oscillations for 1M bi-centrifugal swirl injector at high pressure.

temperatures were recorded for the reverse scheme at high pressure, but the temperature rise during the test was not appreciably greater than for the LOX-outer swirl injectors. The pintle injectors also benefited .from cooling of the face from the flow of LOX through the annulus. A LOX-centered pintle would have likely exhibited a much higher face temperature.

Combustion Stability

Preliminary stability analysis of the high-frequency pressure transducer reveals that the K1 pintle injector, which was designed for the sub-scale OMS condition used in this study, provided stable operation for Cases 1-3. Likewise, the bi-propellant swirl injectors were stable for the OMS operating pressure cases. However for these cases, they often exhibited feed-coupled chug instabilities during start up, presumably due to the likelihood of bubbly LOX flow in the injector at the low pressure conditions. As pressure grew to the steady operating condition, the instability would die out. One injector, the 1M, exhibited high-frequency combustion instability for the higher pressure cases. Note that the 1M injector, as indicated in Table 3, was operated at very high injector pressure drop for the throttled up conditions of Cases 4-6. Figure 18 shows an example plot of power spectral density for the instantaneous chamber pressure. Chamber pressure oscillations in this case were ±30 psi, and so peak-to-peak were 18% of the chamber pressure. Oscillations at about 1800 Hz correspond to the 1L mode of the chamber.

Summary and Conclusions

Marginal LOX quality was seen to have a significant influence on combustion efficiency for both the bi-propellant swirl and pintle injector types tested. Pulsed Shadowgraph imaging proved instrumental in diagnosing the flow phenomena causing lower than expected performance for the swirl injectors. Without this observation of the flow field, it would have been difficult to know with certainty that the spray cones were not mixing as intended or that spray self-pulsations were occurring under some conditions.

The use of a recess to act as a mixing chamber for the swirl injector element appears to be a reasonable solution to the spray cone separation problem caused by poor LOX quality. The large recess forced intimate mixing and made the 2M injector a good performer for all cases tested but without any damage due to overheating any part of the injector and without a severe additional pressure drop penalty. Of significance to the OMS upgrade, this injector combination proved insensitive to LOX quality. LOX cooling of the injector face is also very effective for this arrangement where LOX is run through the outer swirler. Preliminary stability analysis indicates that this injector combination was stable under all conditions tested, including the 2:1 throttled up condition. Of course, the recess length would have to be optimized for the operating conditions of interest so that the most economical and lowest risk solution (minimum recess to provide acceptable performance) could be found. Results suggest that a somewhat shorter recess would probably prove to be optimal.

The K1 pintle injector designed specifically for the OMS project operated both in a stable manner and with high performance. The K1 injector was somewhat sensitive to LOX quality at the low pressure conditions (Cases 1, 2, and 3) unlike the D3 injector. Both injectors saw an increase in C* efficiency with increasing O/F in contrast to the predicted optimum at a mixture ratio of 1.7.

Final conclusions and recommendations are being held until the Aerojet impinging jet injectors are tested under the conditions of this study so that a complete comparison can be made.

On-going and Future Work

A detailed analysis of the high frequency pressure data is underway to fully determine the stability characteristics of the injectors tested. For the pintle injector, hot-fire drop size and velocity measurements are currently being conducted using the Phase Doppler Particle Analyzer. The effect of chamber length on C* efficiency of the pintle injector will be investigated since the chamber length with the scaled down pintle injector does not represent a realistic non-dimensionalized characteristic length.

The performance, heat transfer, and stability characteristics of impinging jet injectors for the OMS condition will be investigated and compared to the results for the bi-propellant swirl and pintle injectors. Aerojet has designed and is fabricating two platelet impinging-jet injectors for use in this study. One is an unlike-doublet impinging splashplate injector and the other is a like-on-like doublet platelet injector similar to the existing OMS engine injector that was built by Aerojet.

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