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Local Heat Flux Measurements with Single and Small Multi-element Coaxial Element Injectors

Gregg Jones*, Christopher Protz†, Brad Bullard†,
NASA Marshall Space Flight Center, Huntsville, AL, 35812

James Hulka‡
Jacobs Sverdrup, MSFC Group, Huntsville, AL, 35812

To support NASA's Vision for Space Exploration mission, the NASA Marshall Space Flight Center conducted a program in 2005 to improve the capability to predict local thermal compatibility and heat transfer in liquid propellant rocket engine combustion devices. The ultimate objective was to predict and hence reduce the local peak heat flux due to injector design, resulting in a significant improvement in overall engine reliability and durability. Such analyses are applicable to combustion devices in booster, upper stage, and in-space engines with regeneratively cooled chamber walls, as well as in small thrust chambers with few elements in the injector. In this program, single and three-element injectors were hot-fire tested with liquid oxygen and gaseous hydrogen propellants at The Pennsylvania State University Cryogenic Combustor Laboratory from May to August 2005. Local heat fluxes were measured in a 1-inch internal diameter heat sink combustion chamber using Medtherm coaxial thermocouples and Gardon heat flux gauges. Injector configurations were tested with both shear coaxial elements and swirl coaxial elements. Both a straight and a scarfed single element swirl injector were tested. This paper includes general descriptions of the experimental hardware, instrumentation, and results of the hot-fire testing for three coaxial shear and swirl elements. Detailed geometry and test results the for shear coax elements has already been published. Detailed test result for the remaining 6 swirl coax element for the will be published in a future JANNAF presentation to provide well-defined data sets for development and model validatation.

I. Introduction

The NASA Marshall Space Flight Center (MSFC) conducted a program in 2005 that focused on improving the reliability and durability of combustion devices for the NASA Space Exploration Mission.[1] The Combustion Devices Injector Technology (CDIT) program focused on improving the technology and the capability to analyze three critical requirement areas in thrust chamber design: 1) injector and chamber thermal compatibility and heat transfer, 2) ignition, and 3) combustion stability. These three areas are the dominating factors that define combustor reliability, and – significantly – engine reliability. Currently, design analysis capability in each area is largely one-dimensional and empirical. The use of advanced analysis techniques such as combustion computational fluid dynamics (CFD) in each area is limited and not yet widespread. Unfortunately, failures are *local*, not global, so use of one-dimensional and empirical models means that developing new designs (or better understanding of current designs) requires extensive full scale testing. The objective of CDIT was to increase the analytical fidelity of each requirement area to include three-dimensional and multi-element effects, and to include the effects of real fluid properties, to be able to evaluate *local* environments. Thus, more detailed information about reliability-critical factors can be made available earlier in the engine development process.

The combustion chamber thermal compatibility, largely defined by the injector, is one of the critical design requirements for any rocket combustor. Real effects of *local* overheating (a three-dimensional phenomenon) are

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* Combustion Specialist, M/S ER32, NASA MSFC, AL, 35812.
† Aerospace Engineer, M/S ER32, NASA MSFC, AL, 35812; Member, AIAA.
‡ Engineering Specialist, MSFC Group, M/S ER32, NASA MSFC, AL, 35812; Senior Member, AIAA.

seldom included in the design process, but are usually factored in by including empirical margins of safety on the thermal and structural analyses. Although it is seldom determined how much these combustors may be over- or under-designed, sometimes other surprising influences are discovered late in the development program. During Space Shuttle Main Engine (SSME) development, for example, blanching of the main combustion chamber wall – an injector effect – severely limited the initial predicted life of the chamber and increased the reusability operating costs due to unanticipated maintenance.

The focus on injector/chamber thermal compatibility in CDIT was to improve the fidelity of heat transfer analysis capability by validating a CFD-based analysis methodology with highly-resolved small-scale experiments, as well as provide relevant design development data. The use of specific experiments for validation of combustion CFD computer codes was part of a long-term CFD development roadmap.[2] The CDIT program consequently had two parts, an experimental task and an analytical tool development task. The experimental task was managed by the NASA MSFC with hot fire testing conducted in the Cryogenic Combustion Laboratory (CCL) at The Pennsylvania State University. The test program gathered local heat flux data using liquid oxygen (LO_2) and gaseous hydrogen (gH_2) propellants. Conventional injection elements were selected to provide varying levels of complexity to the experimental data sets to be generated for combustion CFD code validation. A copper heat-sink combustion chamber highly instrumented with Medtherm coaxial thermocouples and Gardon heat flux gauges was designed and fabricated to resolve local heat flux. The analytical tool development task was also led by the NASA MSFC. Combustion CFD prediction tools were developed to model the injector and combusting flows and to predict the injector face and combustion chamber wall heat flux environment. The NASA MSFC Finite Difference Navier-Stokes (FDNS) code with the real gas model was exercised in the element design phase to provide insight into scaling procedures and the effects of various injector features, as well as to generate pre-test predictions, using axisymmetric and 3-D geometries. Later, the Loci-CHEM code was used for analyzing and comparing to test data.

This paper reports on the hot-fire experiments that were conducted to provide validation data for combustion CFD models used in prediction of combustor heat transfer. Detailed descriptions of the test program[3] and CFD code comparisons[4] have been made for the shear coaxial injectors in the referenced papers. Publication of detailed information on the swirl coaxial injector tests and modeling is planned for the future.

II. Test Hardware

A. Injector Designs

Injector elements were selected with regard toward cryogenic devices for which NASA is interested for Exploration missions. All elements were coaxial, with LO_2 injected from a central tube and gH_2 injected from a concentric annulus. Conceptual designs were developed by the NASA MSFC. Final design drawings were completed and hardware fabricated by The Pennsylvania State University, except for some electro-discharge machined features on some injectors. A top-level summary of the relevant injector configurations tested is provided in Table I.

Element No.	1	2	3	4	5	6	7	8	9
Description	Shear Coaxial Conc.	Shear Coaxial Offset	3-Elem Shear Coaxial Offset	3-Elem Shear Coaxial Offset, Rev'd	Swirl Coaxial Conc.	Swirl Coaxial Conc. Sleeved	Swirl Coaxial 1/2-scale	Swirl Coaxial Scarfed	3-Elem Swirl Coaxial Scarfed
Number of Elements	1	1	3	3	1	1	1	1	3
Oxidizer Post Features	Recess	Recess, off-set	Recess, off-set	Recess, off-set	Flush	Flush	Flush	Scarfed	Scarfed
Fuel Gap Features	Conc.	Non-conc.	Non-conc.	Non-conc.	Conc.	Conc.	Conc.	Conc.	Non-conc.

Note: fuel gap features are "concentric" or "non-concentric"

Table I. Injection element summary

Four shear coaxial elements were tested in this program. The elements were of conventional design with a metering orifice well upstream of the exit. The baseline shear coaxial element (element #1) was scaled from a 40 Klbf thrust chamber program conducted by Rocketdyne for NASA in the National Launch System (NLS) era, for which calorimeter data exist.[5] This element had a concentric annular fuel passage as is typical of the type. The second element (element #2) used this same design but offset the oxidizer post, so that the fuel gap was wide on one side and narrow on the other. The third shear coaxial element was a reduced-size 3-element version of the offset shear element, and was tested in two configurations. The first (element #3) was found during post test inspections to have had one of the three metering diameters smaller than desired. This metering section was subsequently drilled out (element #4), and the injector retested. A cross section of the elements and manifolding of the 3-element injector are shown in Fig. 2. The narrow part of the fuel gap was pointed inboard for all three elements, as shown in Fig. 3. Only data for the first shear coax element will be discussed in this paper. Reference 3 discusses data from the other 3 shear coax elements[3].

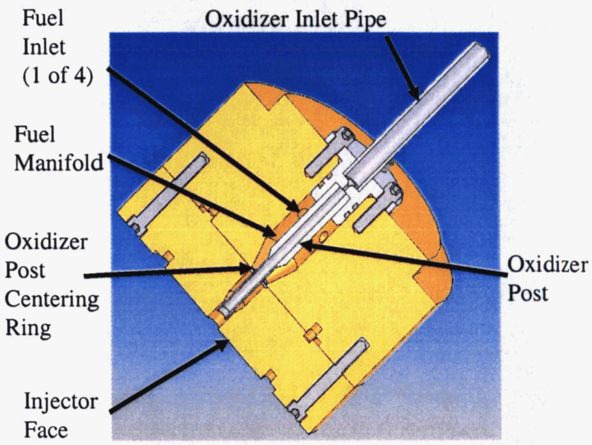

Figure 1. Schematic of single element shear coaxial injector.

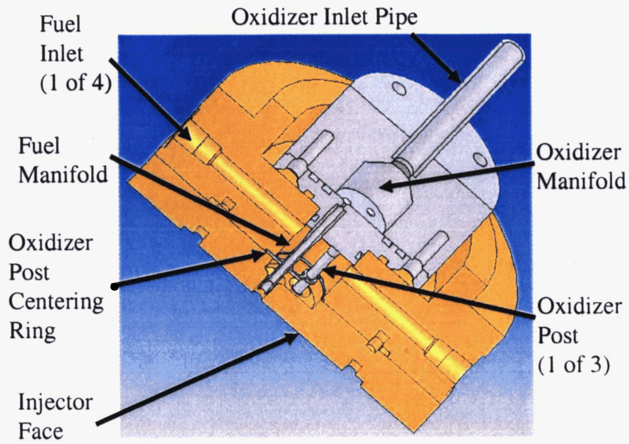

Figure 2. Schematic of 3-element offset shear coaxial injector.

Five swirl coaxial element injectors were tested in this program. All designs were hollow-cone pressure atomizers with tangential entry inlets. The baseline swirl coaxial element (element #5) was scaled from a 40 Klbf thrust chamber program conducted by Pratt & Whitney for NASA also in the NLS era, for which calorimeter data also exist.[6-8] This element had an oxidizer post flush with the injector face and a concentric annular fuel orifice. The first design exhibited poor performance characteristics in the single element chamber, however, probably due to poor selection of inlet geometry, so a second version of this element design was tested with reduced tangential inlet area (element #6). This element demonstrated acceptable characteristics during the test program. A cross section of the element and manifolding of this single element injector are shown in Fig. 3. A reduced-size version of this element, scaled for the same pressure drop at half the flow rate, was also tested (element #7).

A chamber boundary element based on the scarf swirl coaxial design, similar to the one as used in Refs. 6-8, was selected for element #8, using the same swirl inlet geometries and concentric annular fuel orifice as element #5 but including a 45° scarf angle on the oxidizer post exit. The final injector tested was a reduced-size 3-element version (element #9) of this scarf swirl element, with additional changes to the fuel gap width. Only data for the baseline swirl and the baseline scarf element will be discussed in the paper. Data on the other elements is planned for future publications.

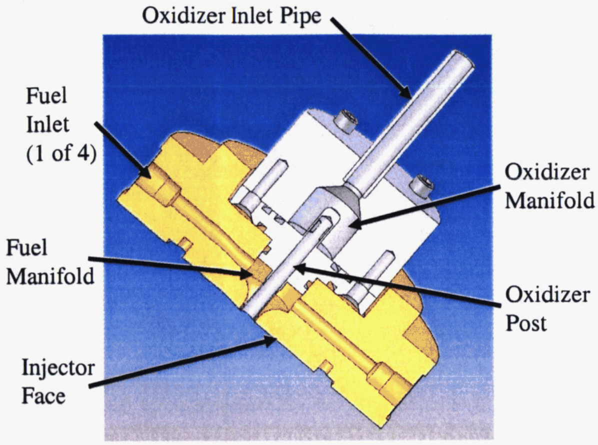

Figure 3. Schematic of single element swirl coaxial injector.

B. Combustion Chamber Design

The combustion chamber assembly was a modular heat sink design constructed of five oxygen-free high conductivity (OFHC) copper cylindrical barrel spool sections and an OFHC copper water-cooled nozzle. The sections mated to each other and to the injector body with a tongue and groove joint and seal and were held together with a hydraulic ram. The inner diameter of the chamber was 1 inch, the outer diameter was 6 inches, and the chamber length from injector face to throat was 14.48". The contraction ratio was 4.96 for all configurations except the reduced-size (half-flow) swirl coax, which had a contraction ratio of 9.96. A simplified schematic is shown in Fig. 4, which includes the lengths and the number and type of heat flux instruments in each spool.

Coaxial thermocouples supplied and installed by Medtherm Corp. of Huntsville, AL, were the primary measurement devices in the main chamber. The Medtherm coaxial thermocouple heat flux gauge consisted of two Copper-Constantan thermocouples imbedded in a 0.250" long by 0.1" diameter plug, as illustrated in Fig. 5. The plug was press fit into the main chamber, and the chamber-side geometry contoured to match the 0.5 inch internal radius of curvature of the chamber. A Type-T thermocouple sliver junction was formed at the tip of the instrument when it was sanded to match the chamber contour. The coaxial thermocouple thus provided two temperature measurements at different radial locations – the chamber inner wall and a recessed location. These coaxial thermocouples were used in a previous hot-fire experiment at the CCL using gaseous propellants.[9-11] Comparisons of these results to CFD calculations have been conducted.[12]

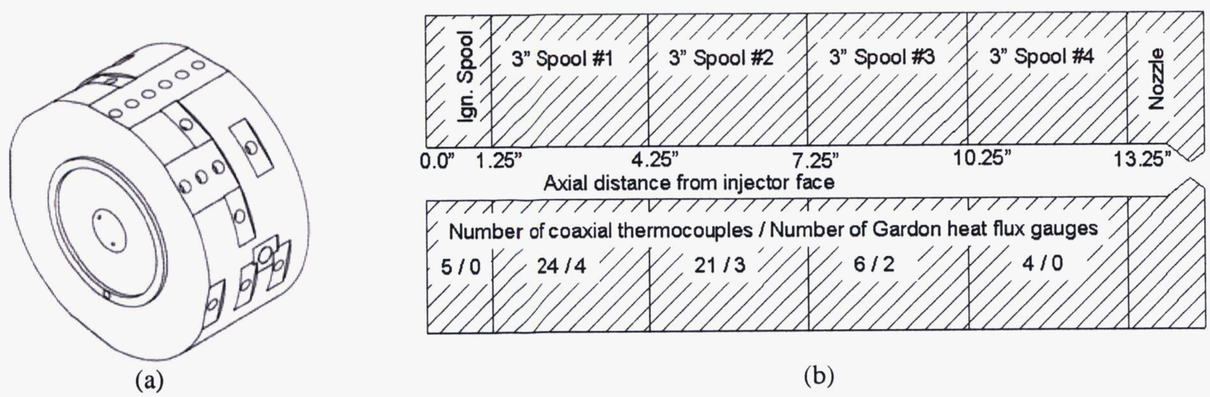

Figure 4. (a) Isometric view of combustion chamber spool piece, showing typical locations for instrumentation. (b) Combustion chamber cross section, listing typical instrumentation in each spool piece.

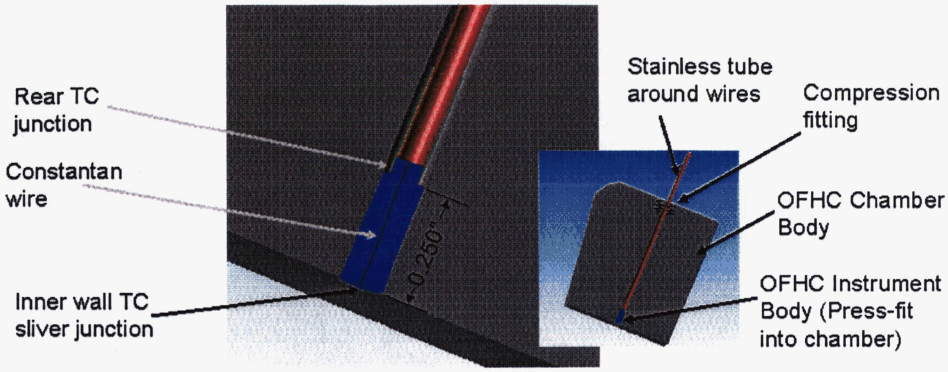

Figure 5. Schematic of Medtherm coaxial thermocouple

Up to 60 coaxial thermocouples were used on any particular test. Fig. 6 shows some examples of cross sectional layouts of instrumentation from various chamber spools. Generally, one side of the chamber had a higher concentration of thermocouples than the other side; for some of the asymmetric elements, the injector was rotated and re-tested so heat fluxes from multiple sides of the element were measured with high resolution.

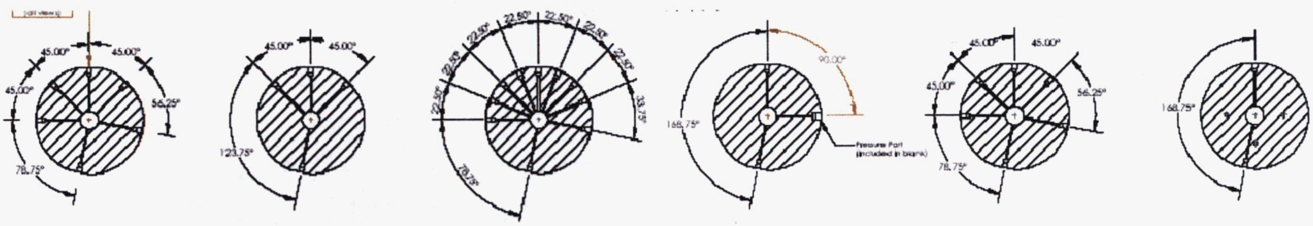

Figure 6. Examples of layouts of heat flux instrumentation in the combustion chamber spools

Several Gardon heat flux gauges were also mounted in the chamber and were used to compare to coaxial thermocouple measurements. The Gardon heat flux gauges had a flat sensing area with a nominal diameter of 0.125", which was not contoured to match the chamber curvature as with the coaxial thermocouples. Data from the Gardon gauges are not included in the results discussed later in this paper.

The rig on the test stand at the CCL at The Pennsylvania State University is shown in Fig. 7.

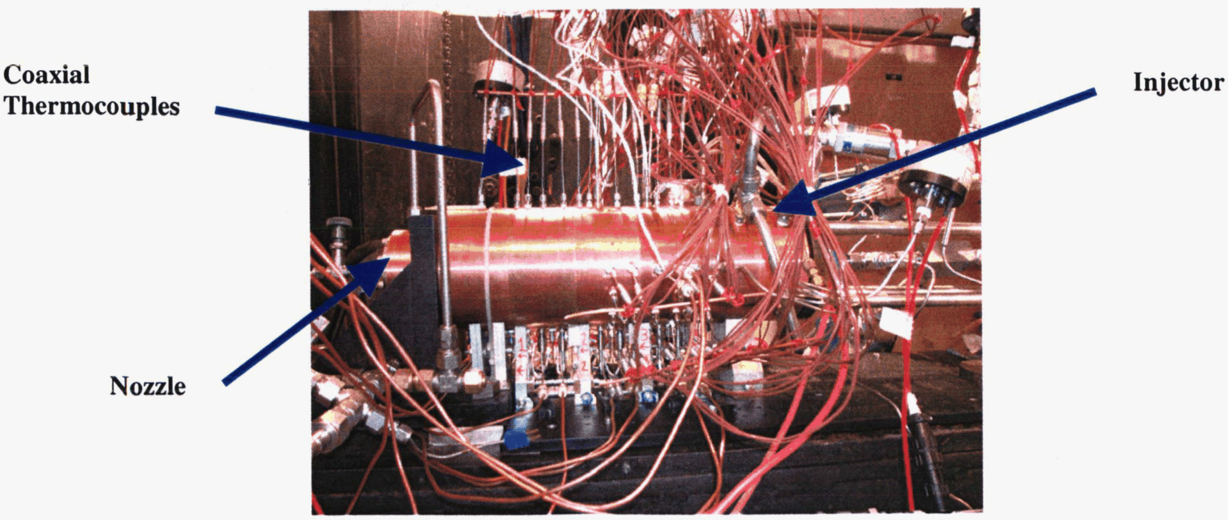

Figure 7. Heat transfer rig installed in the CCL at The Pennsylvania State University

III. Results and Discussion

A. Data Collection and Validation

Heat transfer data were collected for most elements at chamber pressures from 300 to 1200 psia and mixture ratios from 5.0 to 6.5, which cover the thermodynamic state of oxygen from subcritical to supercritical. Since for most tests the throat diameter was unchanged, the element flow rates were reduced when the chamber pressure was reduced, so that the liquid oxygen injection velocity varied linearly with pressure and the gaseous hydrogen injection velocity remained approximately constant for all test conditions. Because the main chamber spools were uncooled, run durations were limited by the heat flux from the hot combustion gases to the chamber wall. Typical run durations at pressure depended upon the injector configuration, and ranged from about 1½-3 seconds at 600 psia chamber pressures, 1-1½ seconds at 800 psia, 1 second at 1000 psia, and ½ second at 1200 psia. Local heat flux was calculated from the local temperatures measured by the Medtherm coaxial thermocouples in the combustion chamber using a 1-dimensional cylindrical conductive heat flux model with a lumped capacitive term for the coaxial thermocouple instrument body. This simplified calculation agreed within 1% of results from a finite element 2-dimensional ANSYS model.

Rigorous data validation analyses are still being conducted with these data. Areas of current investigation include uncertainty, repeatability, accuracy, movement of the coaxial thermocouple plug in the chamber wall, and effects of the calculation procedures. Previous analyses at the CCL for the coaxial thermocouple indicated that the uncertainty in the heat flux measurement estimated from the two temperature measurements was about 0.11 BTU/in^2-sec.[12]

For an initial assessment into accuracy and repeatability, heat flux data from injectors that were rotated were compared to normalized data taken at the same locations but with different gauges on different tests. Both gauge-to-gauge and run-to-run variability were obtained from this analysis. Data from four injectors at three different mixture ratios were used for the assessment. The equation $[\ \Sigma(X_{avg} - X_i)^2/(n-1)\ ]^{0.5}$ was used to calculate an average deviation of about 3% of the highest measured value, where X_{avg} was the average of the two duplicate test data points.

Analysis of heat flux test data from the previous program at the CCL using coaxial thermocouples[9-11] suggested that early in a hot-fire test duration, some of the press-fit coaxial thermocouple plugs as shown in Fig. 7 expanded to create better contact with the combustion chamber. This event was evident by a change in slope of the local temperature increase, caused by the start of conduction of heat from the plug to the chamber body. Results discussed used only heat flux calculated after this time for those sensors where this phenomena was observed.

Over the course of the test program, a few coaxial thermocouple plugs protruded or became recessed into the combustion chamber. These locations were noted and the dimensions from flush with the chamber wall measured. CFD analyses are being conducted to evaluate these effects on the local heat transfer measurement.

The effect of choosing a summary period to calculate heat flux was evaluated. The calculated heat flux was naturally biased lower the later the temperatures were measured during a test since the chamber was a heat sink design. That is, as the inner wall heated up as the test progressed, the heat flux to the wall was lower. The differences in heat flux due to summary period variations in the reduced data were examined for several tests and found to be at most 1.5% from the beginning of the longest averaging span to its end, which is well within the accuracy of the instrumentation.

B. Shear Coaxial Injector Test Results

Detailed data for all shear coaxial injector tests, including element dimensions, heat flux, and temperature data are provided in Ref. 3, along with detailed discussions of the data reduction and analysis. Only the single element shear coax heat flux results will be discussed here to allow comparison with the swirl coax results.

The single element concentric shear coax injector was the first injector tested. Because the concentric shear coaxial single element had a round oxidizer orifice surrounded by a concentric fuel annulus (within +/– 6%), and the element manifolding was designed to mitigate maldistribution effects, the spray and combustion flow fields were expected to be axisymmetric. The level of axisymmetry was analyzed by calculating the square of the correlation coefficient (r^2) of a least squares curve fit of all heat flux measurements in the combustion chamber from the injector face to 5.5" downstream. The r^2 was found to be 0.974, which suggests that the circumferential heat flux for this element was indeed highly axisymmetric over this distance.

The axial heat flux for each test were curve fit with a linear regression analysis using a 4^{th}-order polynomial function with square root, inverse, and exponential terms. A typical example of a curve fit is shown in Fig. 8. Using these curves, the effects of pressure and mixture ratio on heat flux were analyzed. Curves from all single element concentric shear coax tests (including all mixture ratios) are shown in Fig. 9.

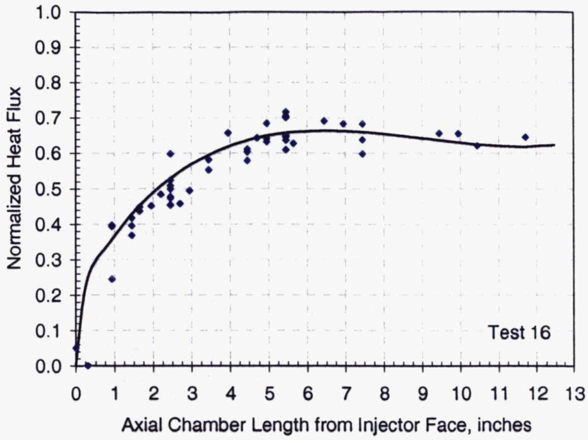

Figure 8. Typical linear regression analysis of single element concentric shear coax heat flux data

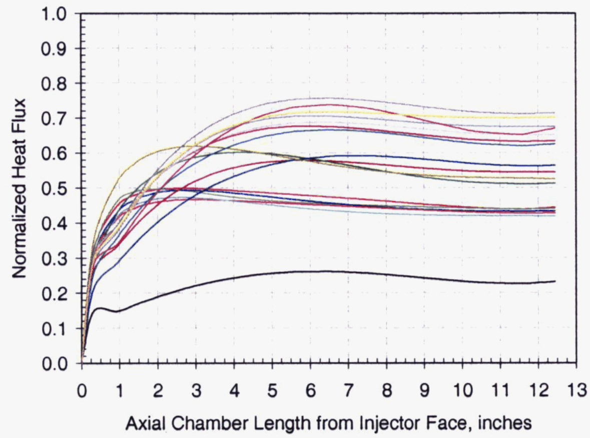

Figure 9. Linear regression analyses of all single element concentric shear coax heat flux data

Typically, heat flux can be scaled by chamber pressure raised to the 0.8 power since empirical data show the heat transfer coefficient can be scaled by chamber pressure raised to the 0.8 power and the combustion temperatures are much greater than the wall temperature.[13] Fig. 10 shows single element concentric shear coax heat flux curves for chamber pressures including 300 psia, 1000 psia, and 1200 psia collapse to a single group, whereas the curves at a chamber pressure of 600 psia collapse to a different group. Fig. 11 shows that the curves for chamber pressures between 700 psia and 900 psia span the two groups. Since these variations occur near the critical pressure of oxygen (736 psia), these out-of family characteristics may be due to the effect of the rapidly changing thermodynamic properties near the oxygen critical pressure on the combustion and heat transfer processes.

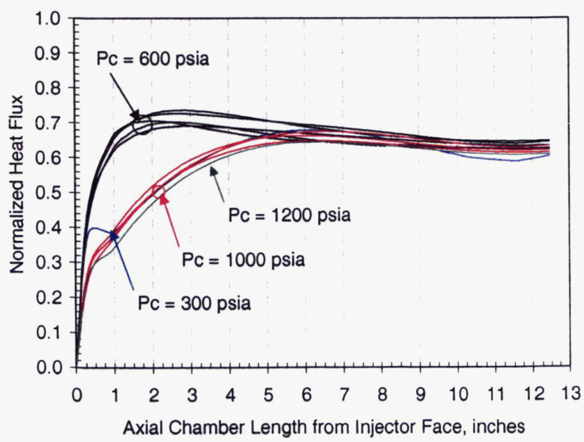

Figure 11. Comparison of various single element concentric shear coax injector heat flux profiles normalized by $Pc^{0.8}$

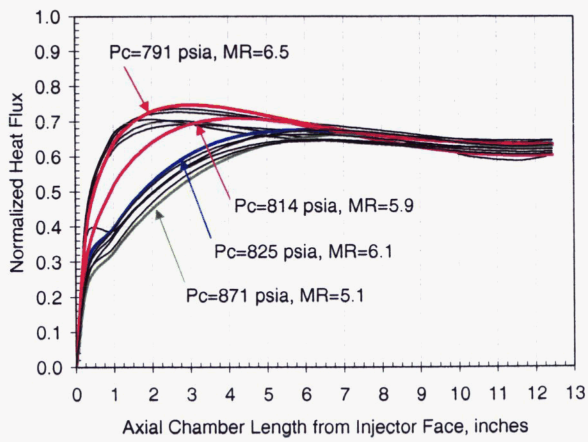

Figure 12. Comparison of all single element concentric shear coax injector heat flux profiles normalized by $Pc^{0.8}$

When the results were grouped by mixture ratio, no strong correlations were found. The variations in heat flux caused by range of mixture ratios from 5.0 to 6.5 were within the accuracy of the measurements

C. Swirl Coaxial Injector Test Results

1. Single Element Full-Size Concentric Swirl Coaxial Injectors

The first swirl coaxial element with a flush oxidizer post and concentric fuel gap exhibited poor performance and low frequency combustion oscillations in the 1-inch diameter combustion chamber. Consequently, the tangential entry inlets of this element were shortened with a sleeve, and the revised element operated with high performance without oscillations. The heat flux profiles for the revised element are shown in Fig. 18, and compared to the heat fluxes from the concentric shear coax element. The swirl coax heat flux resemble the 600 psia data rfom the shear coax in the head end of the chamber, and are ~ 5 to 20% higher in the mixed-out region in the barrel.

The heat flux from the concentric sleeved swirl coaxial element was slightly more axisymmetric than the concentric shear coaxial element. The average r^2 value, of a least squares curve fit of all heat flux measurements in the combustion chamber from the injector face to 5.5" downstream, was 0.983, compared to 0.974 for the shear coax element.

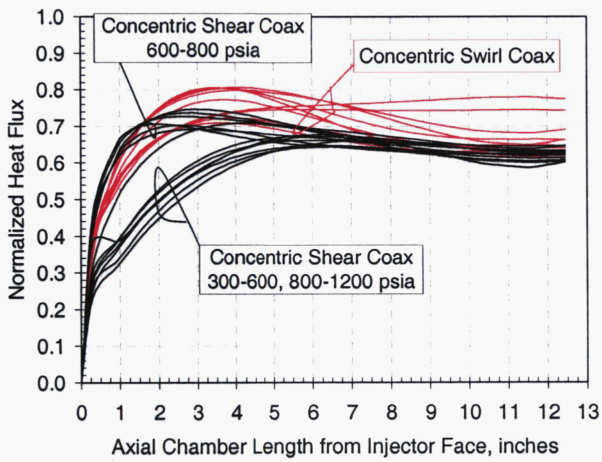

Figure 13. Comparison of heat flux of the single element concentric fuel swirl coax and shear coax configurations.

2. Single Element Scarf Swirl Coax Injector

A single element scarfed swirl coaxial elements (element #8) were tested, as shown in Table I. The single element scarf has a 45-degree scarf post angle on the oxidizer post, and a concentric fuel annulus. Features of scarf post geometry and spray flow are shown schematically in Fig. 14, and a photograph of a typical spray is shown in Fig. 15. The essential attribute of the scarf spray flow is that the oxidizer mass distribution is no longer axisymmetric; a significant portion of the oxidizer mass is distributed to one side of the element, near the "flush" side of the element approximately opposite the "tip" side of the scarf. With a concentric fuel annulus, this results in one side of the element operating at higher mixture ratio than the other side. For typical O2/H2 injector elements operating around MR ~ 6 (below stoichiometric), one side can then operate closer to stoichiometric and subsequently with flame temperatures hotter than a typical element.

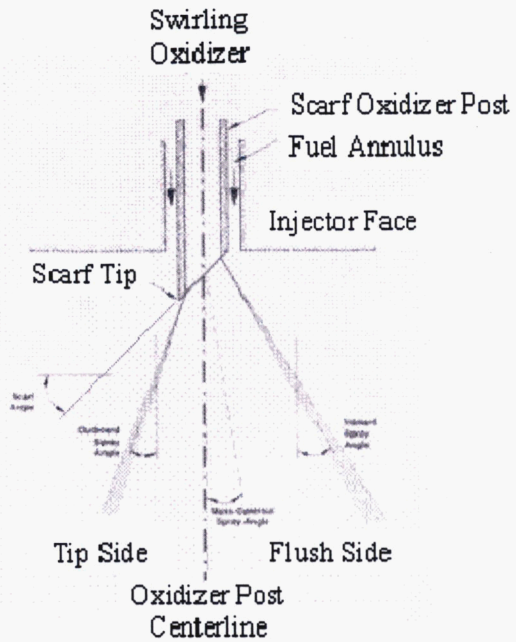

Figure 14. Scarf swirl element nomenclature

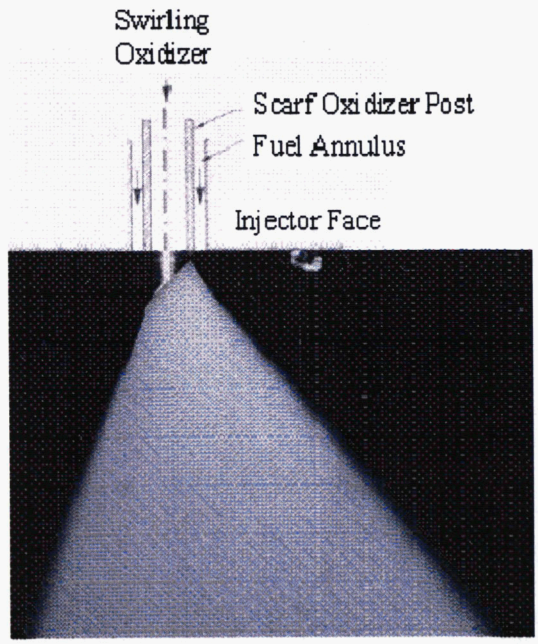

Figure 15. Typical scarf swirl spray photograph

During testing of the single scarf swirl element in this program, very few of the coaxial heat flux gauges on the "hot" side of the element (i.e., facing the flush side) survived the initial tests. To reduce program risk, the scarf tests with the injector rotated so that the flush side faced the highest concentration of heat flux gauges were moved to the very end of the overall program. Unfortunately by then, many the gauges were not recoverable. Consequently, little data from the flush, high heat flux side of the scarf element was collected. Fig. 16 compares heat flux from the tip side and the flush side; the data available shows that the flush side had a dramatically higher heat flux. Fig. 17 compares the tip side of the scarf swirl coax to the concentric swirl coax. The peak heat flux was reduced by 20% and the overall heat load reduced by 25% in the injector end. Slightly lower heat flux even extended all the way down the barrel.

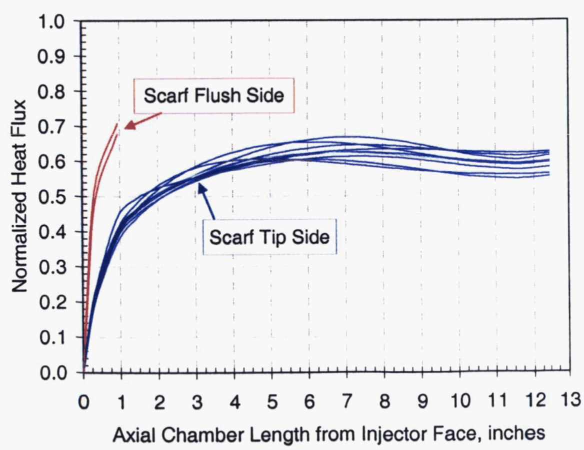

Figure 22. Scarf swirl element heat flux on the cold and hot side of the chamber

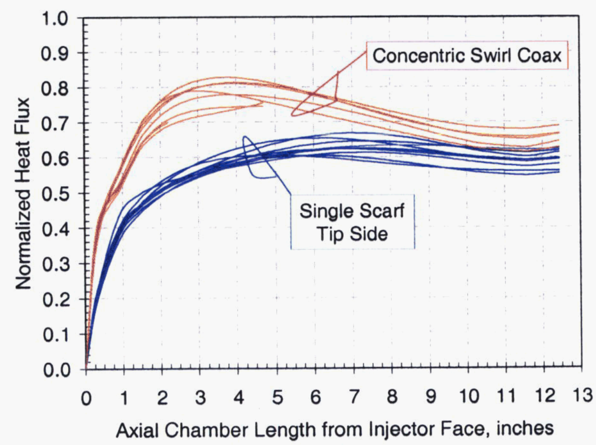

Figure 23. Sleeved swirl coax 1D averaged data vs. cold side scarf swirl data normalized by Pc

The single element scarf swirl coax was the only element which had reduced heat flux along the whole barrel length of the chamber. Certainly, the heat flux on the tip side was reduced due to a reduction in mixture ratio at the wall, which persisted down the length of the chamber wall. However, the single element heat flux reduction in the barrel was only half of the 30% heat flux reduction measured during multi-element 40 Klbf testing.[6-8] It seems likely that some of the mixture ratio bias was mixed out by the flow redistribution (radial winds).

While an efficiency cannot be accurately calculated for these tests, efficiencies can be compared between injectors. The C* efficiency of the single element sleeved swirl element was 7% higher than the single element scarf swirl.

IV. Summary and Conclusions

The Combustion Devices Injector Technology (CDIT) program at the NASA MSFC provided a significant and unique collection of hot fire heat flux test data for injector element designs as expected to be widely used on liquid propellant rocket engines for the NASA Vision for Space Exploration missions.

The thermal compatibility/heat transfer task was designed to provide a unique capability to measure *local* heat transfer and use these unique data for validation of prediction of local heat transfer by combustion CFD codes. A 1"-diameter combustion chamber highly instrumented with Medtherm coaxial thermocouples and heat flux gauges has been used to hot-fire test axisymmetric and non-axisymmetric shear coaxial and swirl coaxial injection elements, including single- and multi-element configurations.

Both shear coax and swirl coax elements with concentric fuel gaps were found to have circumferential heat flux variations less than 3%, with the swirl coax heat flux slightly more uniform. The heat flux from the concentric swirl coax was higher than the concentric shear coax along the entire measurement section of the chamber.

The scarf swirl were found to provide reductions typically heat flux ~ 10 to 20 % at the head end of the chamber. These reductions did not persist down the whole length of the chamber.

Acknowledgments

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References

[1]Jones, G., Protz, C., Trinh, H., Tucker, P.K., Nesman, T., and Hulka, J., "Status of the Combustion Devices Injector Technology Program at the NASA MSFC," AIAA Paper No. 2005-4530, July 2005.

[2]Tucker, K., West, J., Williams, R., Rocker, M., Canabal, F., Robles, B., Garcia, R., and Chenoweth, J., "Using CFD as a Rocket Injector Design Tool: Recent Progress at Marshall Space Flight Center," Fifth International Symposium on Liquid Space Propulsion (CD-ROM), Chattanooga, TN, 2003.

[3]Jones, G., Protz, C., Bullard, B., Hulka, J., Santoro, R., Pal, S., Woodward, R.D., and Marshall, W., "Local Heat Transfer Measurements in a LO_2/H_2 Single Element Injector," 53rd JANNAF Propulsion Meeting / 2nd Liquid Propulsion Subcommittee Meeting, Monterey, CA, December 5-8, 2005.

[4]Tucker, P.K., Lin, J., West, J.S., and Chenoweth, J. "Steady-State Combustion CFD Analyses of Local Heat Transfer for LO_2/H_2 Injectors," 53rd JANNAF Propulsion Meeting / 2nd Liquid Propulsion Subcommittee Meeting, Monterey, CA, December 5-8, 2005.

[5]Elam, S.K., "Low Element Density Injector Test Program P329," NASA Marshall Space Flight Center Propulsion Laboratory Report, NASA MSFC, AL, June 7, 1996.

[6]Dexter, C.E., and Best, P.J., "Testing of a Pratt & Whitney LOX/H2 40K Subscale LOX Swirl Coaxial Injector at MSFC TS116," NASA Marshall Space Flight Center Propulsion Laboratory Report TR-EP73-91-03, NASA MSFC, AL, March 18, 1991.

[7]Petersen, E.L., Rozelle, R., and Borgel, P.J., "Characterization and Wall Compatibility Testing of a 40K Pound Thrust Class Swirl-Coaxial Injector and Calorimeter Combustion Chamber," AIAA Paper 91-1873, June 1991.

[8]"STE Thrust Chamber Technology Main Injector Technology Program and Nozzle Advanced Development Program, Final Report," United Technologies Report FR-23116, Contract NAS8-37490, October 31, 1993.

[9]Santoro, R.J., Lin, J., Marshall, W.M., Pal, S., West, J., Wang, T.S., Williams, R., Chen, Y.S., and Lee, C.P., "GO2/GH2 Injector Testing and Analysis," Paper 3.2, NASA Marshall Space Flight Center Spring Fluids Workshop, Huntsville, AL, April 13-15, 2004.

[10]Marshall, W.M., Pal, S., and Santoro, R.J., "Benchmark Wall Heat Flux Data for a GO_2/GH_2 Single Element Combustor," AIAA Paper No. 2005-3572, July 2005.

[11]Santoro, R.J. and Pal, S., "Validation Data for Full Flow Staged Combustion Injectors," Final Report for NASA Contract Grant NAG8-1792, The Pennsylvania State University, 2005.

[12]Lin, J., West, J.S., Williams, R.W., Tucker, P.K., and Chenoweth, J.D., "CFD Code Validation of Wall Heat Fluxes for a GO_2/GH_2 Single Element Combustor," AIAA Paper No. 2005-4524, July 2005.

[13]Bartz, D.R., "Turbulent Boundary-Layer Heat Transfer from Rapidly Accelerating Flow of Rocket Combustion Gases and of Hot Air," Adv. Heat Trans., Vol. 2, 1965.