

INJECTOR ELEMENT CHARACTERIZATION METHODOLOGY

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ABSTRACT

Characterization of liquid rocket engine injector elements is an important part of the development process for rocket engine combustion devices. Modern non-intrusive instrumentation for flow velocity and spray droplet size measurement, and automated, computer-controlled test facilities allow rapid, low-cost evaluation of injector element performance and behavior. Application of these methods in rocket engine development, paralleling their use in gas turbine engine development, will reduce rocket engine development cost and risk. The Alternate Turbopump (ATP) Hot Gas Systems (HGS) preburner injector elements have been characterized using such methods, and the methodology and some of the results obtained will be shown.

INTRODUCTION

Development of combustion devices for liquid propellant rocket engines and related applications is frequently a pacing item in the engine development process. Requirements for high impulse efficiency, injector/chamber thermal compatibility, combustion stability, producibility, and maintainability must be balanced against each other and suitable compromises made in the design of the injector and the injection elements. Control of development risk and cost prohibits making element and injector design decisions based upon full-scale injector tests. Sub-scale tests at the individual element and sub-assembly level, and at ambient and elevated pressure levels, are an attractive and low-cost method of obtaining information usable for full-scale injector design. Use of sub-scale tests requires intelligent choice of test conditions, measurement techniques, and measured parameters.

The requirements of combustion system designers for the capabilities of the injection systems has only partly been matched by the capabilities of the instruments used to characterize injection system performance. Technology in high-performance gas turbine engine fuel system design and development has advanced at a rapid pace over the past two decades, driven by requirements for reduced exhaust emission levels, more stringent operating environments, and increased competition in the marketplace. Efforts of fuel system vendors to design, characterize, and develop fuel systems meeting the design criteria imposed by the engine manufacturers has resulted in the implementation of a new generation of characterization instruments and procedures.

APPROACH AND OBJECTIVES

Application of these characterization methods to the Alternate Turbopump (ATP) Hot Gas Systems (HGS) is an important part of the design of the injectors and injection elements. The injectors for the ATP HGS will serve as gas generators for ground test of the Alternate Turbopump units until SSME-type Government Furnished Property (GFP) injectors can be made available from the manufacturer. For these ground tests with HGS injectors, minimizing program risk is of paramount importance so as to avoid disruption to the ATP qualification effort. The program plan for these injectors included element characterization tests to screen improvements to the elements and to establish injection element performance baselines.

The ATP HGS and GFP injectors employ concentric-type injection elements, an example of which is shown in Figure 1. Concentric injectors employ a central liquid injection nozzle, or post, and a surrounding fuel injection sleeve. The characterization program examined the behavior of the fuel and oxidizer portions of the element by themselves and as combined in the element assembly. The test objectives were to

- Identify design improvements for the HGS elements
- Characterize the behavior of the HGS and GFP elements
- Provide information usable as initial conditions for Computational Fluid Dynamics (CFD) codes to predict the temperature distributions entering the ATP turbines.

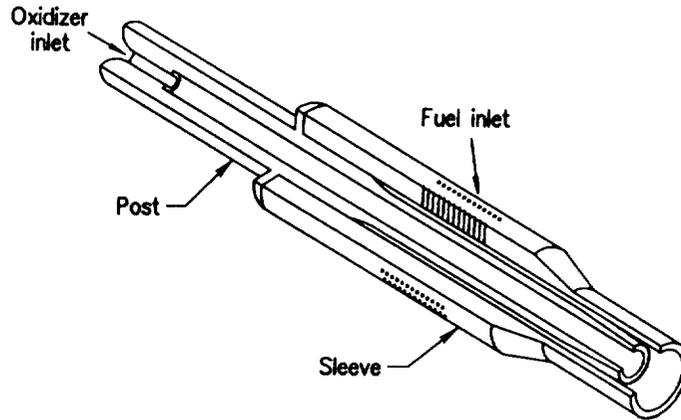


Figure 1: Concentric Injector Element

Subsequent discussion will concentrate upon the implementation of the test plan. Included are the choice of test fluids, test conditions, and types of tests and measurements. Selected results will be shown.

TEST FLUIDS

Testing at ambient conditions makes inclusion of the cryogenic effects of liquid oxygen extremely difficult. Use of liquid nitrogen as a test fluid is an attractive option where the cryogenic effects are of importance. Even at the supercritical pressures typical of the SSME or advanced cryogenic engines, most of the initial atomization and fluid mixing processes take place at liquid oxygen temperatures below critical. The oxygen thus behaves as a liquid. Test fluids which approximate the liquid oxygen density, surface tension, and viscosity are appropriate. Including test fluids with a wide range of properties aids in extrapolation to hot-fire conditions. Test fluids such as water, chlorofluorocarbons (CFC's), and hydrocarbons are reasonable test fluids for ambient and elevated, moderate pressure tests. Extrapolation to the high-pressure engine or hot-fire test environment is facilitated by correlating measured quantities with fluid and operating variables.

Table I
Fluid Properties Comparison

Fluid: Property	LOX	Water	MIL-C-7024	Chloro- difluoro- methane
Specific gravity	1.188	1.000	0.770	1.195
Viscosity (cp)	0.417	1.005	0.901	0.198
Surface tension (dyne/cm)	11.16	73.05	22.70	8.00

Table I compares the properties of test fluids selected for the ATP HGS injection element characterization effort with those for liquid oxygen. MIL-C-7024 Type II fluid is a refined Stoddard solvent widely used to simulate gas turbine fuels. It and water are used for ambient pressure tests. For elevated-pressure tests, chlorodifluoromethane is a very close match to liquid oxygen in all respects. Together, these three test fluids cover a wide range of fluid properties, with the liquid oxygen properties falling within the range of properties represented. At 70F, the vapor pressure of chlorodifluoromethane is about 135 psia, so that tests must be conducted at pressure levels in excess of this to avoid flash vaporization. Other reasonable choices for a test fluid include 1,1,2-trichloro-1,2,2-trifluoroethane and 1,2-dichloro-1,1,2,2-tetrafluoroethane.

TEST CONDITIONS

A number of relations describing the atomization of liquids are available (1-5). These relate spray Sauter mean diameter (SMD) or mass median diameter (MMD) to fluid and operating variables, and to injection element configuration and dimensions.

Lorenzetto and Lefebvre (1) investigated atomization of a cylindrical jet of fluid recessed within an annulus of high-velocity gas, Figure 2. Liquid physical properties, gas/liquid ratio, gas velocity, and element dimensions were varied independently over wide ranges and the resulting spray Sauter mean diameters correlated with these variables:

$$SMD = 0.95 \frac{(\sigma \dot{m}_L)^{0.33}}{U_R \rho_L^{0.37} \rho_A^{0.30}} \left(1 + \frac{\dot{m}_L}{\dot{m}_A}\right)^{1.70} + 0.13 \mu_L \left(\frac{d_0}{\sigma \rho_L}\right)^{0.5} \left(1 + \frac{\dot{m}_L}{\dot{m}_A}\right)^{1.70}$$

The fluid physical properties are represented by the density, ρ_L ; the viscosity, μ_L ; and the surface tension, σ . Operating variables are represented by the gas/liquid velocity ratio, U_R , and by the liquid and gas mass flow rates, \dot{m}_L and \dot{m}_A . Gas density, ρ_A , and the liquid jet diameter, d_0 , complete the variables.

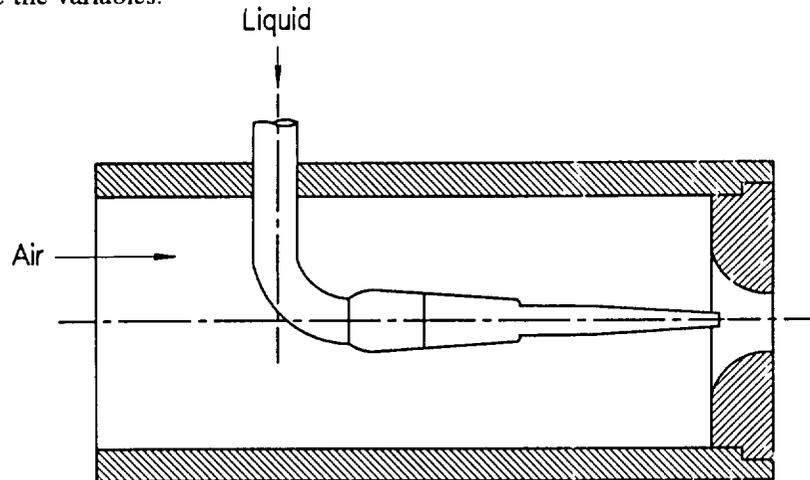


Figure 2: Lorenzetto-Lefebvre Experiment For Plain Jet Atomization

Fraser, Dombrowski, and Routley (2) investigated atomization by a cylindrical sheet of fluid surrounded by an annulus of high-velocity gas. Their droplet-size correlation is

$$SMD = 6 \times 10^{-6} + 0.0187 \frac{\sigma^{0.5} v_r^{0.21}}{\rho_A^{0.5} (aD_L + a^2)^{0.25}} \times \left[1 + 0.065 \left(\frac{\dot{m}_L}{\dot{m}_A}\right)^{1.5} \right] \left[\frac{Q_L}{U_p^3 (0.5U_r^2 - U_r + 1)} \right]^{0.5}$$

As with Lorenzetto and Lefebvre, liquid properties are included through the fluid surface tension, viscosity, and density. The last two are included through the ratio of fluid kinematic viscosity to that of water, ν_R . Gas density, the air/liquid velocity ratio, v_r , the liquid tangential velocity, U_p , the liquid volumetric flow rate, Q_L , and the liquid/gas mass flow ratio are also represented. Physical dimensions include the diameter of the liquid sheet at the point of discharge from the element, D_L , and the radius to the liquid/gas interface, a .

Figure 3 shows operating conditions for the ATP HGS and GFP fuel preburners over a range of hot-fire conditions simulating engine power levels from 50% to 115% of Rated Power Level (RPL). Values are given for the injection element mass flow ratio (O/F), oxidizer/fuel velocity ratio, and momentum ratio. These quantities must be matched in any test which is used to evaluate the atomization of the liquid oxygen by the gaseous hydrogen, or to assess the effects of momentum interchange between the two propellants upon spray distribution.

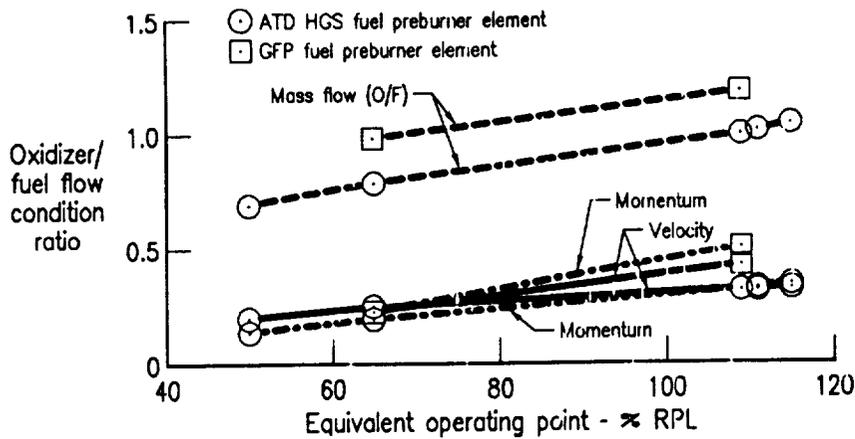


Figure 3: Flow Condition Ratios For Hot-Fire Tests

Atomization and mixing processes which depend upon the relative mass flows and velocities between the liquid and gaseous phases are not correctly represented by ambient tests. Figure 4 shows typical results when setting conditions for ambient tests. The Mach number of the air (simulating the hydrogen) was set to the same value as at hot-fire conditions. The velocity of the test liquid (simulating the liquid oxygen) was set to a value which matches the hot-fire liquid/gas velocity ratio. The resulting injection pressure drops and densities give liquid/gas mass flow and momentum ratios which are well in excess of the hot-fire conditions. Matching mass flow or momentum ratio also leads to mismatches in the other quantities.

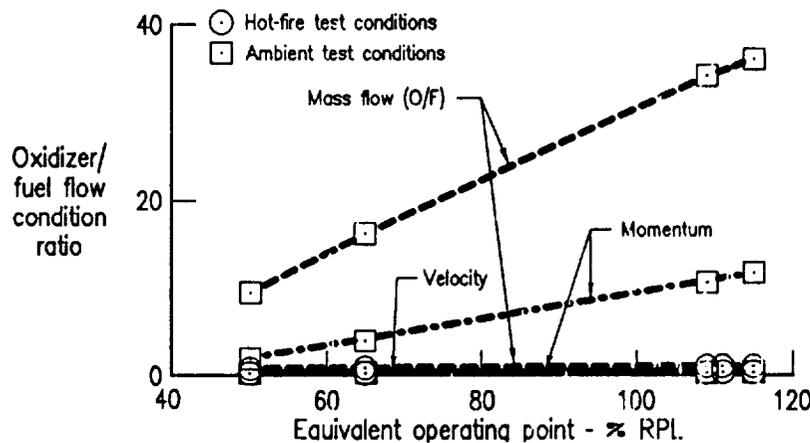


Figure 4: Flow Condition Comparison For Ambient Tests

For a self-atomizing injection element, however, many important quantities can be measured and evaluated by testing the element at the actual hot-fire pressure drops. Comparative evaluation of spray shape, flow uniformity, manufacturing and assembly tolerance variations, element effective flow areas, and element configuration can be carried out.

The selection of operating conditions for elevated, moderate pressure tests permits close matching to hot-fire conditions. Test section pressures can be selected to match test element gas densities to the hot-fire fuel density. The higher molecular weight of the test gas (air) offsets the higher pressure of the hydrogen gas in the hot-fire condition. For the ATP HGS element characterization tests, a test chamber pressure of 560 psia results in air densities that are nearly identical to the hot-fire hydrogen densities at the 109%-115% RPL power points. Matching of hydrogen densities at the 50%-65% RPL power points results in test chamber pressures near 215 psia. This approaches the vapor pressure of many candidate chlorofluorocarbons and would result in vaporization of large quantities of the test fluid. The droplet sizes would decrease with distance from the element due to evaporation to a greater extent than at the 560-psia level.

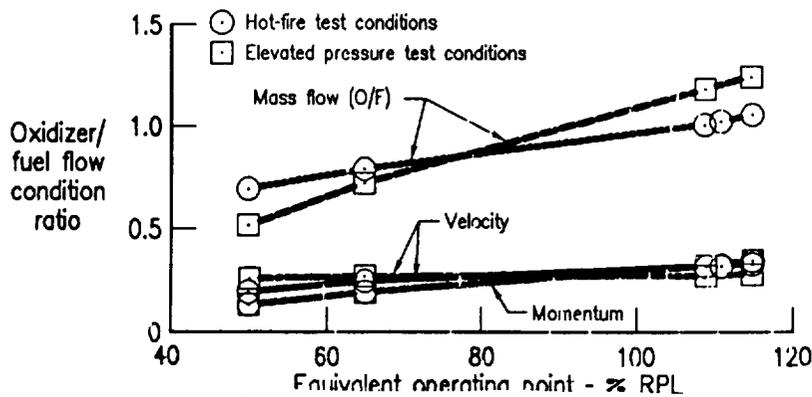


Figure 5: Momentum Ratios Matched To Hot-Fire Values

Figure 5 shows results of setting test conditions for elevated-pressure tests at 560 psia test chamber pressure, using chlorodifluoromethane as the test liquid. The air Mach number was set equal to the hot-fire hydrogen injection Mach number. For this figure, however, the liquid flow conditions were set to those which match the hot-fire oxidizer/fuel momentum ratio. The resulting injection pressure drops and densities give liquid/gas mass flow and velocity ratios which are nearly the same as for the hot-fire conditions. Matching of the liquid/gas velocity ratios results in mass flow and momentum ratios which do not match hot-fire conditions as well, Figure 6. Resulting flow conditions for the ATP HGS and the GFP injection element characterization tests are shown in Table II.

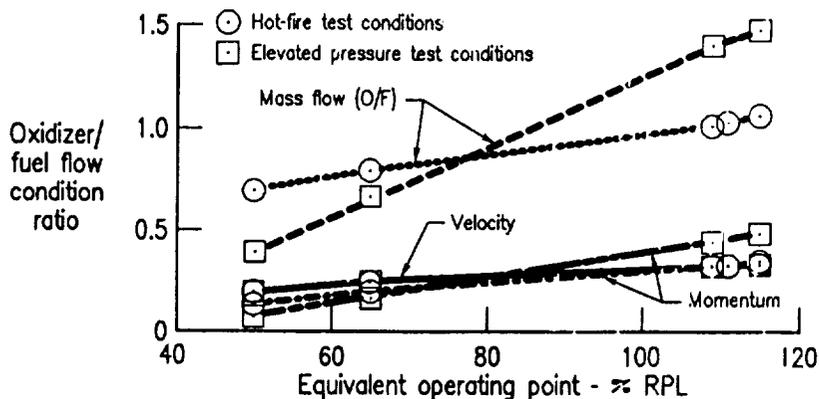


Figure 6: Velocity Ratios Matched To Hot-Fire Values

Table II
Injection Element Test Conditions

Environment	Element	Level	Pressure Drop (PSID)				
			Gas	Liquid Primary	Secondary		
Ambient	HGS	50%	0.296	32.0	1.2		
		65%	0.282	53.0	3.2		
		109%	0.321	41.0	18.0		
		115%	0.321	33.0	20.0		
		50%	0.	400.0	15.0		
		65%	0.	645.0	40.0		
		09%	0.	575.0	200.0		
		115%	0.	395.0	245.0		
	GFP	65%	0.98		31.0		
		109%	1.20		197.0		
		65%	0.		355.0		
		109%	0.		1495.0		
		Elevated	HGS	50%	11.3	89.0	3.3
				65%	10.7	99.0	5.9
109%	12.2			46.0	20.0		
115%	12.2			36.0	23.0		
GFP	65%		37.0		65.0		
	109%		46.0		180.0		

TEST SELECTION

The propellant flows within a rocket engine injector are complex. Flowpaths within the injector manifolds and cavities directly affect the flow conditions at each injection element. Element characterization cannot include every effect of the propellant flowpath. It must concentrate upon only those features of injection element behavior which are intrinsic to the element itself. Inclusion of other propellant flowpath effects is quite properly the objective of injector characterization efforts. However, injector flowpath effects can and should be treated as appropriate variations in the propellant pressures and temperatures supplied to the elements.

The test matrix for the ATP HGS and GFP injection elements is shown in Table III. The initial order of the tests was selected to provide design-specific information as early as possible. Purely characterization data were obtained after the element design was frozen. As with any test program, modification and rearrangement of the tests became necessary because of test hardware availability, technical difficulties with certain tests, and resolution of questions on particular aspects of injection element behavior identified during preceding tests.

Table III
ATP HGS/GFP Injection Element Characterization Tests

Test	Type	Element	Environment
1	Fuel velocity distribution	1X HGS	Ambient
2	Spray quality, fuel and oxidizer effective flow areas	1X HGS	Ambient

3	Evaluation of element variations on spray shape	1X HGS	Ambient
4	Liquid spray patternation	1X HGS	Ambient
5	Alignment tolerance assessment, internal flow visualization; effect of combined flow on fuel velocity distribution	3X HGS	Ambient
6	Spray droplet sizing	1X HGS	Ambient
7	Spray quality, fuel and oxidizer effective flow areas	1X GFP	Ambient
8	Fuel velocity distribution	3X GFP	Ambient
9	Spray droplet sizing (Deleted)	1X GFP	Ambient
10	Liquid spray patternation	1X GFP	Ambient
11	Spray droplet sizing	1X HGS	560 psia
12	Spray droplet sizing	1X GFP	560 psia
13	High-speed motion picture of spray formation	1X HGS, GFP	Ambient

MEASUREMENT AND INSTRUMENTATION

Quantities measured for the elements during these tests included

- Fuel and oxidizer flow metering effective areas, and variations with supply pressure
- Circumferential and radial variations in mass flow and velocity resulting from element configuration and configuration variations
- Effects of element manufacturing dimensional tolerances
- Element internal flow behavior
- Spray droplet size and size distributions
- Effects of element or injector assembly tolerances

Flow Calibration

Fuel and oxidizer flow metering effective areas were obtained using flow benches. Because some of the flowrates were comparatively small, particular care had to be exercised in setting up and conducting the tests to control leakage, flow meter bias and precision errors, and flow contaminants.

A major objective for the flow area measurements of the ATP HGS element fuel sleeve element was to determine whether the fuel flow was metered at the inlet area, exit area, or a combination of the two. For the ATP element, the fuel inlet area is nominally four times the exit area so that in principle the fuel is metered only at the exit. However, dimensional variations in the parts result

in variations in the ratio of inlet area to exit area. Systematic variation of the appropriate dimensions, Figure 7, showed that the discharge coefficient was invariant and the exit annulus is the controlling area. In production, individual fuel sleeves and oxidizer nozzles may need to be individually matched for uniform mixture ratio. For the fuel sleeve, dimensional inspection alone is sufficient to determine hardware acceptability. Flow calibration of individual fuel sleeves is not required.

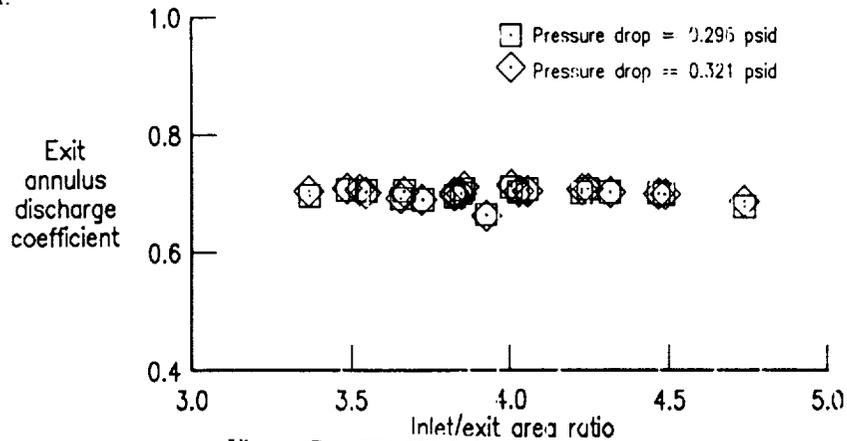


Figure 7: ATP HGS Fuel Sleeve Flow Calibration

Flow calibration of the ATP oxidizer nozzle confirmed the expected variation of orifice discharge coefficient with flow split (primary flow/total flow), Figure 8. This information is used in the power balance model calculations of injector and valve performance as a function of equivalent power level. The reduction in secondary port effective area with increasing flow split (decreased secondary flows) reflects the desired exchange of momentum between the primary and secondary flows at the low secondary pressure drops associated with low secondary flow.

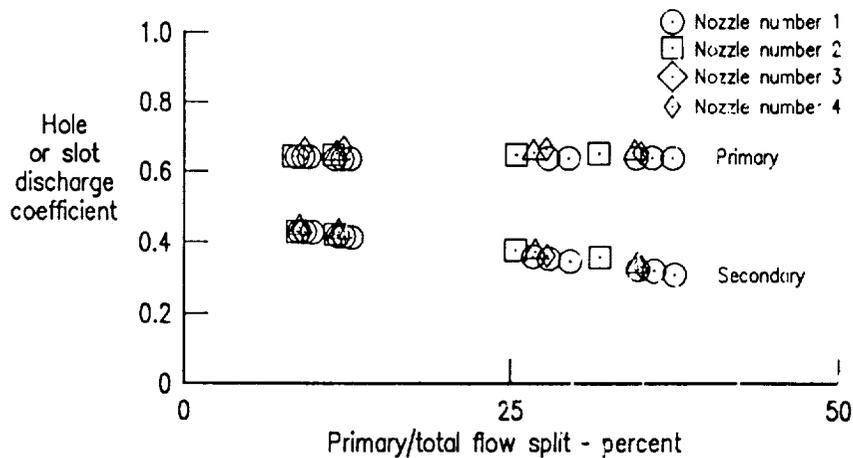


Figure 8: ATP HGS Lox Nozzle Flow Calibration

Injected Liquid Spray and Fuel Gas Distribution

Circumferential and radial variations in injected mass flow are measured using patternators. The use of patternators in evaluating spray distribution has received increased attention in recent years. A new generation of automated patternators have been developed and applied to spray characterization (6-9). The most modern patternators use a built-in computer to control test duration, fluid measurement, and data recording, and data reduction.

Two types of patternator are in common use. The zone patternator collects the entire volume of discharged fluid into an array of contiguous compartments. A large number of compartments increases the spatial resolution of the patternator, but introduces fluid handling and plumbing difficulties. Typical zone patternators provide comparatively coarse spatial resolution and provide little information on radial spray distribution.

Radial-arm patternators provide greater spatial resolution at the expense of total sample collection. These have a number of linear collector arrays, crossing at a central point. Rotation of the element relative to the radial arms increases the number of circumferential locations. The radial arm patternator returns both radial and circumferential information about the spray.

Representative zone and radial-arm patternator results for the ATP HGS injection element are shown in Figure 9. The variation of flow is within acceptable limits. For the radial patternator, the local normalized maximum flow (largest volume of collected fluid along each arm, divided by the average of these maxima) and normalized total flow (total volume of collected fluid along each arm, divided by the average of these totals) show nearly identical distribution. The zone patternator shows good agreement with the radial patternator.

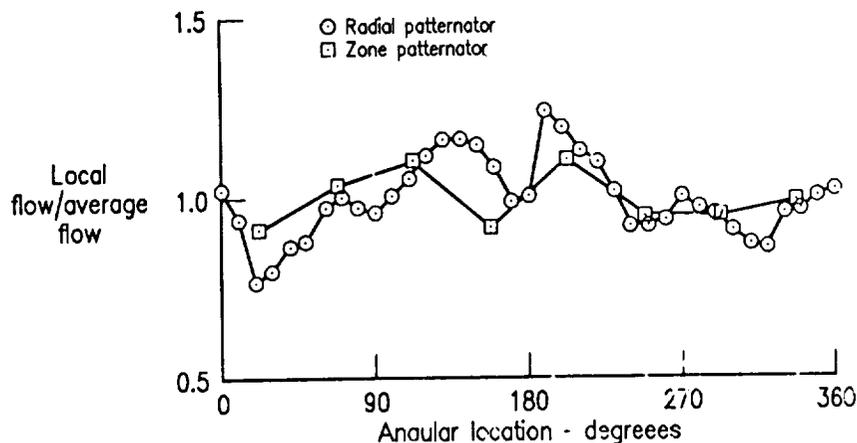


Figure 9: ATP HGS Element Patternation Results

Information on fuel gas injection velocity and mass flow distribution has traditionally been more difficult to obtain. Pitot probes interfere with the flow patterns of small injection elements and cannot reliably be used in regions of strongly recirculating flow. The advent of commercially-available one and two-component Laser Doppler Velocimeter (LDV) instruments now gives the investigator the capability of non-intrusive measurement of forward and reverse velocities with spatial resolution on the order of 100 microns. LDV measurements comparing three variations of the ATP HGS fuel sleeve design are shown in Figure 10. Low circumferential variations in fuel velocity are desirable for mixture ratio management; however, a degree of variation is beneficial as a mixing aid. LDV measurements of the gas radial velocity profiles inside the CAF element, between the start of the LOX post external taper and the exit of the fuel sleeve, are shown in Figure 11. Lower gas velocities are encountered immediately adjacent to the outer wall of the LOX post.

Element Internal Flow Behavior

Evaluation of the internal flow behavior for the ATP and CAF injection elements used 3X scale metal and transparent plastic flow models of the injection elements. Use of large-scale models has several benefits:

- Visualization of important flow features is improved.

- Sensitivity to dimensional variations is reduced.
- Capability is providable for parts interchangeability for configuration variation.

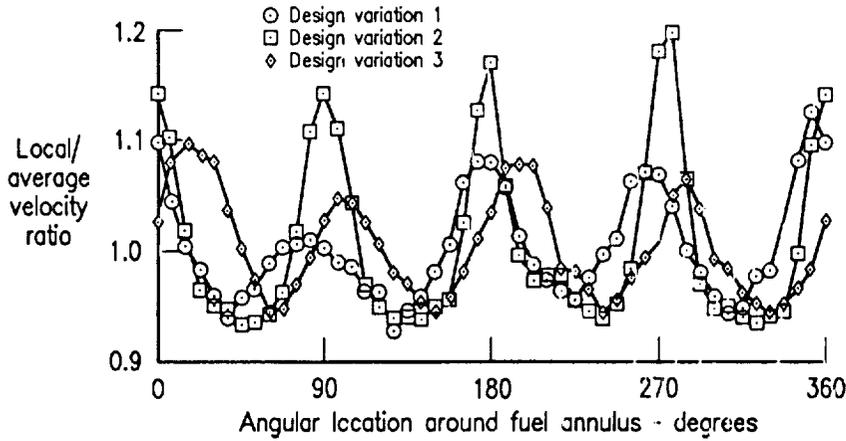


Figure 10: ATP HGS Fuel Sleeve Exit Velocity

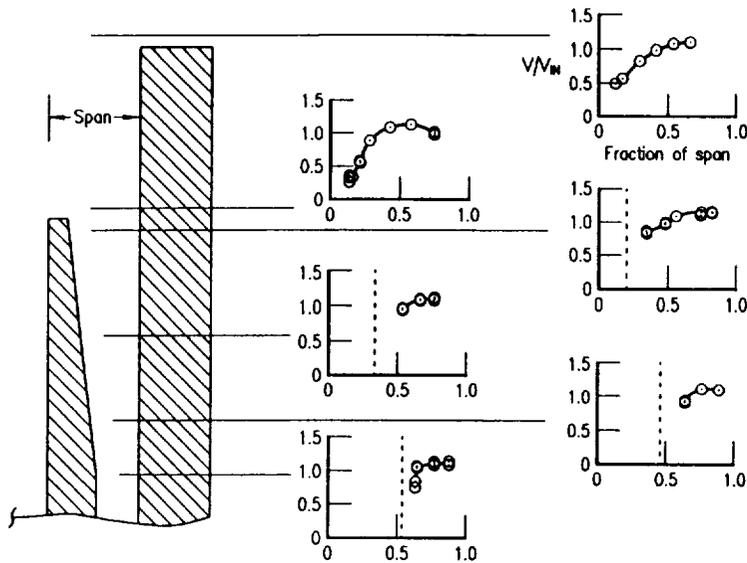


Figure 11: CAF Fuel Sleeve Radial Velocity Profiles

The 3X transparent model of the CAF element was submerged in a water tunnel for observation of the flowfields in the fuel cup region at low Reynolds number. Blue and yellow dyes were used to trace flows from the LOX post and fuel sleeve. No flow separation along the LOX post taper was seen. The end of the LOX post did support a sizable rearward-facing separation bubble, which extended downstream for five to seven times the width of the rear face. This separation bubble was identifiable by the entrainment of both dye and air bubbles. Downstream of the separation bubble, the appearance of green color signaled the mixing between the streams of dye from the LOX post and fuel sleeve.

Spray Droplet Size Distribution

Within the past fifteen years, measurement of spray droplet size and size distribution has moved away from direct collection techniques (10-14) to first visualization/scanning (15-18) and thence to laser diffraction and Doppler methods (19-21). Commercial equipment for both diffraction and Doppler methods is readily available and verified in a variety of environments (22-28). Numerous spray analysis efforts have been appearing in the recent literature (29-37).

Issues involving characterization of the dense sprays typical of rocket engine injection elements must still be addressed carefully during element characterization programs. For diffraction-based instruments the following issues are of importance:

- Beam obscuration
- Multiple diffractions
- Beam steering from refractive index differences
- Selective spatial redistribution of droplets through spray/gas interaction

For Doppler-based instruments important issues include the following:

- Simultaneous passage of more than one droplet through the sampling volume
- Failure of large droplets to pass through the sampling volume during the sample interval

Spray droplet size measurement of the ATP and CAF injection elements has to date only been done with a diffraction-based system. The particular model of instrument allowed correlation of the light intensities with either an assumed Rosin-Rammler (two-parameter) cumulative droplet size distribution or a so-called model-independent (fifteen-parameter curve fit) solution.

Correlation of measured droplet Sauter mean diameter (SMD) for the ATP element is currently in progress. Data currently available for the ATP element include tests at ambient test conditions with water and MIL-C-7024 test fluids. High-pressure test results with CFC's are not yet available. Atomization at ambient test conditions for the CAF element is unrealistically poor and the resulting spray is opaque. This test was deleted from the program.

Effects of Element or Injector Assembly Tolerances

Evaluation of the effects of element configuration variations, manufacturing dimensional tolerances, and element or injector assembly tolerances used actual-size injection elements and the 3X scale flow models of the ATP element. The 3X injection element model incorporated provision for changing the LOX nozzle tip configuration and for varying the axial and radial alignment of the nozzle and fuel sleeve. This flow model was used to quantify the effects of element misalignment and to investigate the element internal flow characteristics. For the ATP element, misalignment was shown to have no effect on the spray configuration. In particular, there was no evidence of spray impingement on the fuel sleeve even with the most severe misalignment. The extreme axial misalignment corresponded to a recess of 0.020 inches, while the most extreme radial misalignment corresponded to a two-thirds reduction in the fuel annulus gap.

SUMMARY

Properly-conducted injection element characterization tests are an important tool in reducing rocket engine development time and risk. The ATP IIGS element characterization program identified significant design improvements in time for these to be incorporated into the injector design. The tests also gave valuable insight into differences in the performance and operating characteristics

of both the ATP and CAF elements. Finally, test and evaluation methodologies have been implemented and refined, and their successful use in future rocket engine technology and development efforts is assured.

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