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Photographic Observation of Reactive Stream Impingement

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This paper describes the results of an experimental study conducted to develop injector design criteria for coping with reactive stream separation (RSS), that is, blowapart, experienced with hypergolic Earth-storable propellants. RSS operating regimes were identified for single-element liquid rocket injectors using high-speed color photography. N_2O_4/MMH, N_2O_4/A-50, and N_2O_4/N_2H_4 propellants were tested using nine different injector element types. Three hundred and fifty-six (356) tests were run over a wide range of chamber pressure, propellant temperature, and injection velocity. The chamber pressure and fuel orifice Reynolds number are used to correlate injector operating regimes of mixing and RSS. These correlations define injector design criteria for coping with RSS. The mechanisms controlling RSS are described and illustrated.

Nomenclature

A_S = fuel evaporation surface area, ft^2
D = diffusion coefficient, ft^2/s
D_S = droplet diameter, ft
D_F = fuel orifice diameter, in.
K_V = mass transfer coefficient, s^{-1}
Nu_M = Nusselt number for mass transfer
P_C = chamber pressure, lb/ft^2
P_V = propellant vapor pressure, lb/ft^2
R = gas constant, ft-lb/lb-R
Sc = Schmidt number
Re = Reynolds number
T = fuel vapor film temperature, °F
T_F = fuel injection temperature, °F
T_O = oxidizer injection temperature, °F

Introduction

HIGH-PERFORMANCE liquid-propellant rocket injectors typically use unlike fuel and oxidizer stream impingement to produce propellant atomization and mixing. Design criteria for these injectors is generally based on nonreactive cold-flow correlations. Rupe's[1] work is the most definitive and widely used. It describes the relationship between propellant spray mass and mixture ratio uniformity and the injector design and operating conditions. However, experience has shown that unlike impingement of the highly reactive hypergolic Earth-storable N_2O_4/amine fuels does not always produce the spray field characteristics predicted by these cold-flow correlations. Under certain operating conditions, the impingement mixing process is disturbed by rapid combustion within the impingement interface.[2] This combustion phenomena, termed reactive stream separation (RSS) or blowapart, causes striation of the propellant spray into zones of unmixed oxidizer and fuel. Striation of the propellant sprays reduces the injector mixing efficiency and, hence, performance.[3] RSS modifies the cold-flow mass and mixture ratio distributions which alter the injector thermal compatibility and stability characteristics.

RSS effects have been observed with a wide range of injector element types, including unlike doublets, quadlets, triplets, and like-on-like.[2-7] RSS-related performance, stability, and compatibility problems were encountered during development of both the Apollo SPS and Space Shuttle OMS and RCS engines. The Apollo and Space Shuttle engine development experience has shown that these cold-flow design tools do not account for RSS combustion phenomena which can control engine performance.

Although several studies[7-18] have been conducted over the past 10 years in an effort to develop design criteria for RSS avoidance, none were totally successful. Several RSS models were postulated, but none were able to account for all of the observed behavior. Conflicting data and experimental limitations were responsible.

The objective of this work was to develop an understanding of the physicochemical mechanisms controlling RSS so that design criteria could be established. The approach taken was to photographically observe single-element injector combustion of N_2O_4/MMH, N_2O_4/A-50, and N_2O_4/N_2H_4 propellants. Photographic observation was selected, since previous work had shown that RSS is difficult to quantify on the basis of normal engine performance measurements. Single-element injectors were used to provide an unobstructed view of the impingement zone. The single-element injectors allowed a wide range of parameters to be tested so that true parameter influences could be determined. The hot firings were conducted in a specially constructed photographic chamber. High-speed color motion pictures were used to identify the occurrence of RSS.

Experimental Hardware and Test Setup

The test chamber is equipped with four optical quality quartz viewing ports and removable injectors and nozzles, as shown in Fig. 1. The removable copper nozzles provide the desired operating pressures up to 1000 psia. The injector element configurations tested are shown in Fig. 2. These include four conventional unlike doublet injectors, two conventional triplet injectors, and three platelet injectors. Platelet injectors are fabricated by bonding together a stack of thin metal sheets which have etched flow passages. A simulation of the Space Shuttle RCS injector is included in the unlike doublets, and a simulation of the Space Shuttle OMS engine like doublet platelet injector is included in the platelet injectors. These elements include both coherent stream and atomized spray impingement injector types.

The coherent jet impingement elements include the unlike doublet and the triplet. The atomized spray impingement elements include the transverse like-on-like (TLOL), the x-doublet (XDT), and the splashplate platelet elements. The TLOL atomized spray fans are formed by self-impingement of the propellant streams as with a conventional like-on-like injector. The XDT element produces an atomized spray fan

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by self-impingement within the platelet stack. The splashplate element uses solid wall impingement to produce the atomized spray fan.

The test chamber was set up as shown in Fig. 3. Standard rocket test instrumentation was used to measure pressures and temperatures. The propellant flow rates were determined using the measured injector pressure drops and the injector hydraulic admittances.

The N_2O_4 oxidizer and MMH, A-50, and N_2O_4 fuels were all propellant grade in conformance with the applicable military standards. No fuel additives were used.

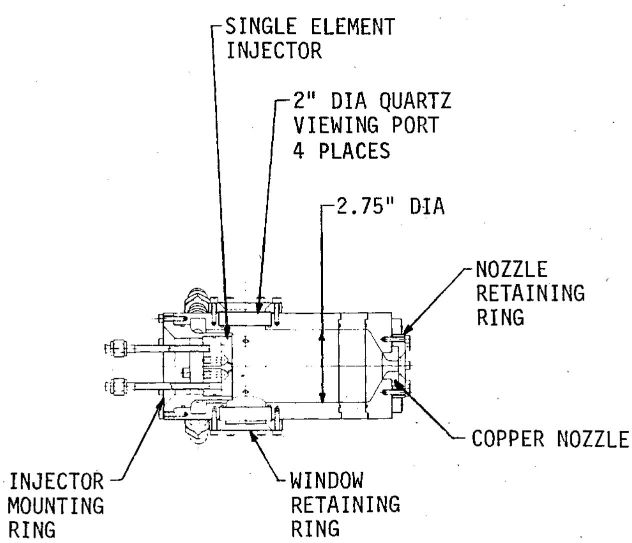

Fig. 1 Photographic test chamber and single-element injector.

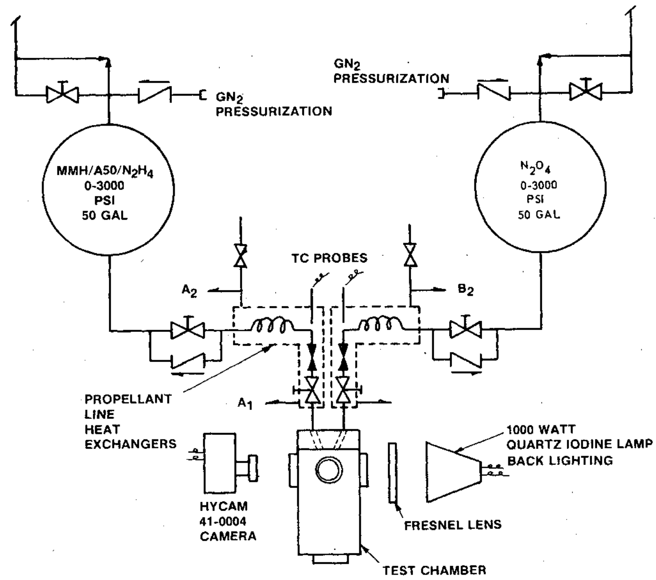

Fig. 3 Test setup and photographic equipment.

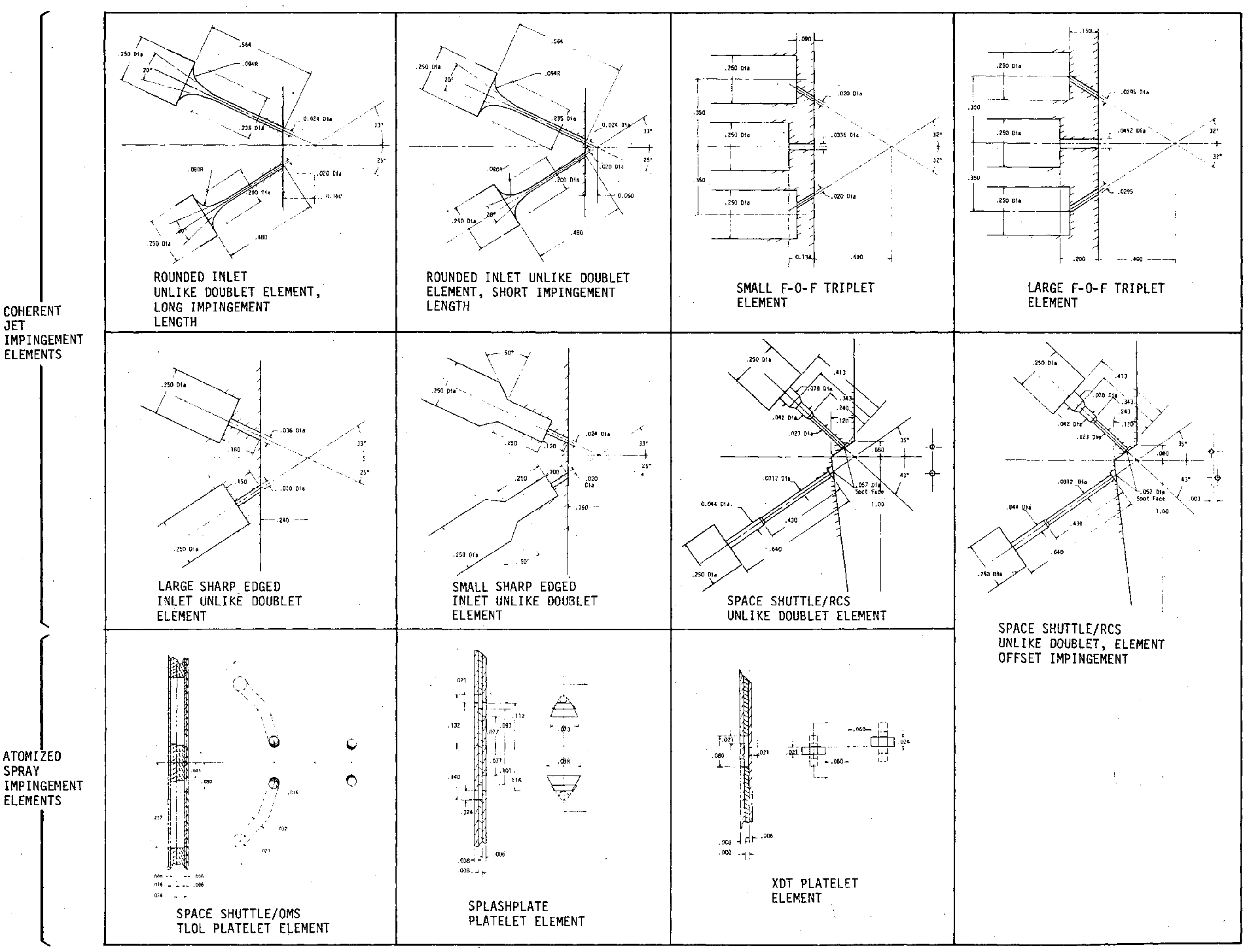

Fig. 2 Injector element configurations.

Photographic Equipment and Technique

The photographic combustion characterization was accomplished using the equipment shown in Fig. 3. The photographic equipment is centered around a Hycam model 41-0004 rotating prism high-speed movie camera. This camera is capable of varying the frame exposure time independent of the film frame rate. This feature makes it possible to obtain exposures of a few microseconds at relatively low frame rates.

Lighting of the spray field was accomplished with one quartz iodide lamp to backlight the spray area with three smaller lamps to light the top, bottom, and front. A balance between the front and back lighting is essential for high-quality photos. Kodak ektachrome type EFB tungsten (3200 K) color film was used.

The photographic technique developed in this work is based on the use of high-intensity lighting to illuminate the combustion field. The flame light is overpowered by high-intensity lamps so that the film doesn't "see" it. Development of this photographic technique was essential to the successful identification of RSS regimes.

Results

RSS Regimes

Regimes of RSS were identified for the injector elements listed in Table 1. These regimes were determined after repeated viewing of the high-speed movies by at least two analysts. Four modes of impingement, as illustrated in Fig. 4, were identified from the film.

1) *Penetration* occurs at low injection velocity, low fuel temperatures, and low chamber pressure and is evidenced by overpenetration in the spray field. High oxidizer con-

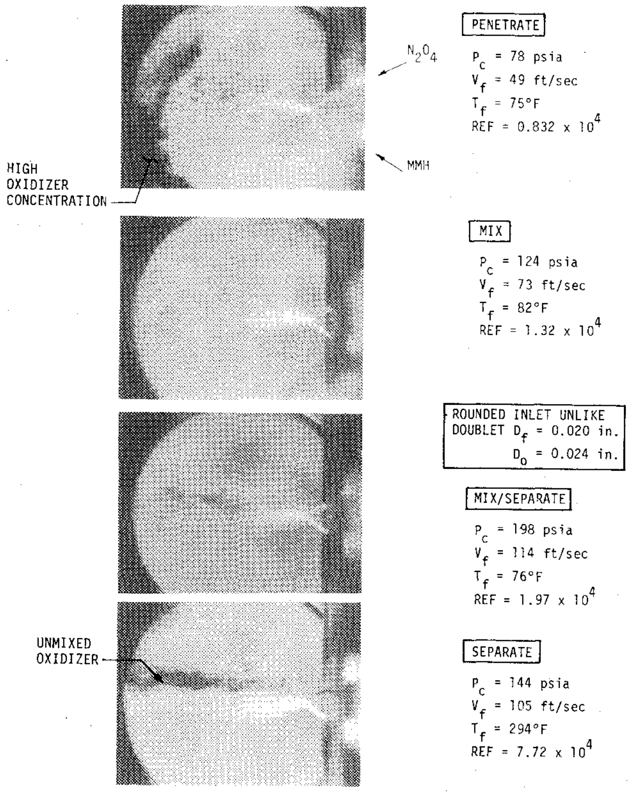

Fig. 4 High-speed photography defines four modes of reactive stream impingement.

Table 1 Summary of injector elements and test conditions

Injector element	Fuel	P_c, psia	V_F, ft/s	V_O, ft/s	T_F, °F	T_O, °F	Mixture ratio
			Coherent jet impingement				
Rounded inlet unlike doublet, $D_f = 0.020$	MMH	80-1000	35-160	30-111	55-300	55-150	1.60-1.70
	A-50	90-1000	50-162	40-114	60-85	55-80	1.60-1.70
Small F-O-F triplet, $D_f = 0.020$	N_2H_4	60-300	40-165	34-130	65-160	68-76	1.60-1.70
	MMH	80-210	40-100	30-70	70-300	60-145	1.60-1.70
Large F-O-F triplet, $D_f = 0.029$	MMH	80-195	30-78	32-65	75-300	68-150	1.60-1.70
Small sharp-edged unlike doublet, $D_f = 0.020$	MMH	68-396	35-216	26-150	68-245	68-104	1.60-1.70
	N_2H_4	75-392	40-160	34-125	73-173	66-82	1.60-1.70
Large sharp-edged unlike doublet, $D_f = 0.030$	MMH	80-310	34-174	30-110	68-265	66-136	1.60-1.70
	N_2H_4	84-410	30-175	30-150	66-80	64-85	1.60-1.70
			Atomized spray impingement				
Space Shuttle/RCS unlike doublet, $D_f = 0.023$	MMH	83-247	28-119	25-142	50-137	47-123	1.36-3.15
Space Shuttle/RCS unlike doublet, offset impingement, $D_f = 0.023$	MMH	114-193	61-106	36-105	75-87	68-80	1.45-3.06
Space Shuttle/OMS TLOL platelet injector,	MMH	43-195	29-127	26-112	65-231	62-83	1.44-1.81
$D_f = 0.028$	N_2H_4	104-397	38-120	40-112	71-155	70-78	1.43-1.96
XDT platelet, $D_f = 0.021$	MMH	81-194	42-100	32-80	68-291	62-162	1.60-1.70
Splashplate platelet, $D_f = 0.021$	MMH	81-192	40-104	32-80	71-288	71-154	1.60-1.70

centrations are noted in the lower portion of the spray field. Penetration has been reported in earlier cold-flow work and was also observed in this work using propellant simulants. Penetration is a consequence of the nonreactive momentum exchange mixing process.

2) *Mixing* is observed at moderate injection velocities, moderate fuel temperatures, and moderate chamber pressures. It is evidenced by a highly uniform spray field that looks similar to a nonreactive spray field.

3) *Mix/separate* occurs at the onset of RSS. It is evidenced by a slightly nonuniform spray field.

4) *Separation* is observed at higher injection velocities, higher fuel temperature, and higher chamber pressures. It is evidenced by highly nonuniform spray fields with distinct regions of unmixed fuel and oxidizer.

The test results show that: 1) A-50 and N_2H_4 fuel behave like MMH fuel in regard to RSS; 2) increasing the fuel velocity, chamber pressure, or fuel temperature promotes RSS; 3) atomized spray impingement elements promote RSS; and 4) no pops or cyclic combustion phoenomena were observed.

Model Correlation

RSS is correlated with a vaporization-controlled model by plotting chamber pressure P_c vs fuel orifice Reynolds number Re_F as shown in Figs. 5 and 6. The A-50 and N_2H_4 fuels both exhibit the same RSS limit as the MMH fuel. The fuel properties were found to be controlling, since the fuel is more difficult to vaporize than the oxidizer. Since the oxidizer parameters show only weak correlations, they were eliminated from the final correlation.

The RSS dependence on chamber pressure and fuel Reynolds number can be related to a vaporization-controlled combustion mechanism, as shown in Fig. 7, by making these assumptions: 1) the combustion gas generation rate prior to impingement must exceed some minimum rate for RSS to occur; 2) combustion gas generation occurs through gas phase reaction only; and 3) combustion gas generation rate is limited by the fuel vaporization rate, since it is the least volatile propellant.

The vaporization rate is related to the fuel vapor pressure and fuel vaporization surface area through the mass transfer process[19]:

$$\dot{W}_V = A_S K_V P_c \ln[P_c/(P_c - P_v)] \tag{1}$$

The movie films show that the fuel stream surface is rapidly heated to the saturation temperature, such that the vapor pressure is essentially equal to the chamber pressure. The mass transfer coefficient is related to the Reynolds number through the Ranz and Marshall[20] Nusselt number correlation for evaporation:

$$Nu_m = D_S RTK_V/D = 2.0 + 0.6\, Sc^{1/3} Re^{1/2} \tag{2}$$

With these conditions, the fuel vaporization rate at which RSS occurs is a function of the fuel vaporization surface area and the Reynolds number. The fuel vaporization surface area for coherent jets consists primarily of the jet surface which is generally fixed. However, the movies show that as the jet velocity is increased, a point is reached where the jet begins to shed microdroplets as shown in Fig. 7. When this happens, the fuel vaporization surface area increases significantly. The jet shedding is correlated with the jet Weber number or

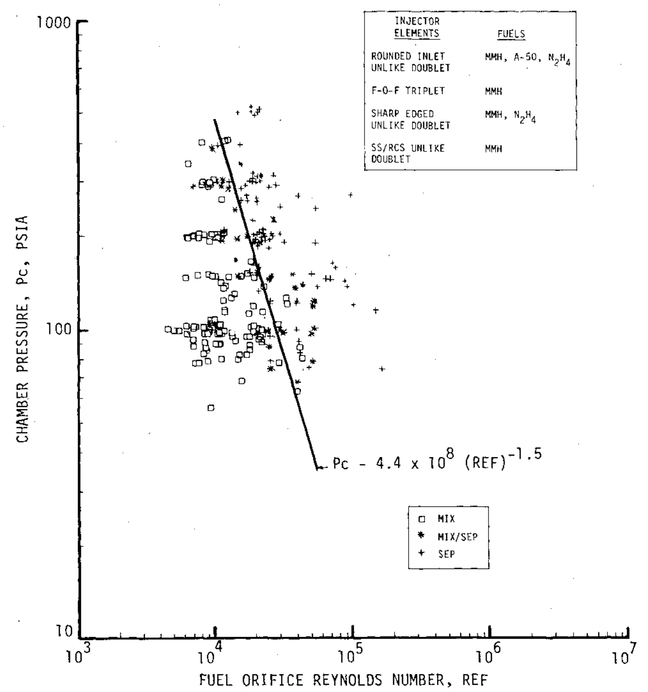

Fig. 5 Vaporization model correlates RSS for coherent stream impingement injector element.

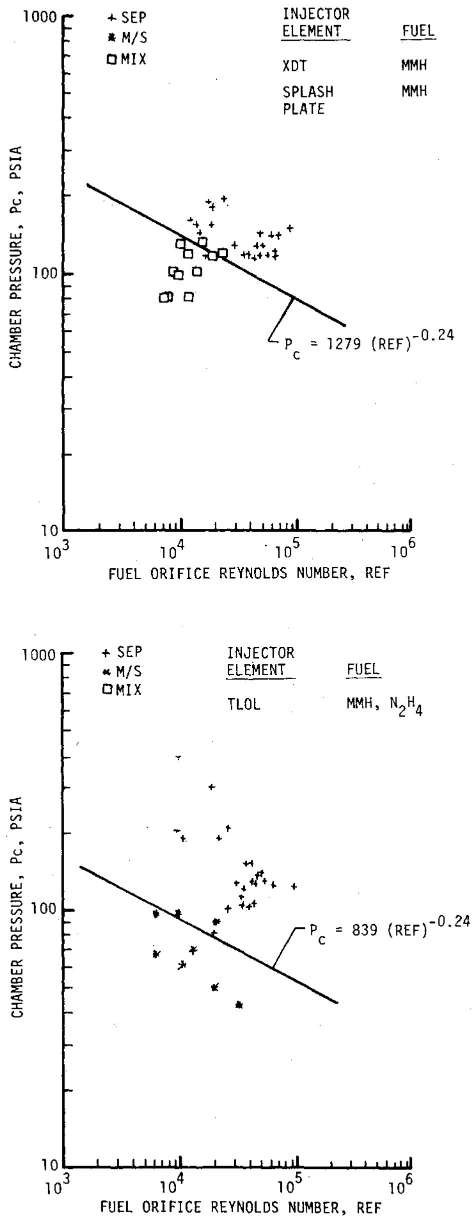

Fig. 6 Vaporization model correlates RSS for atomized spray impingement injector elements.

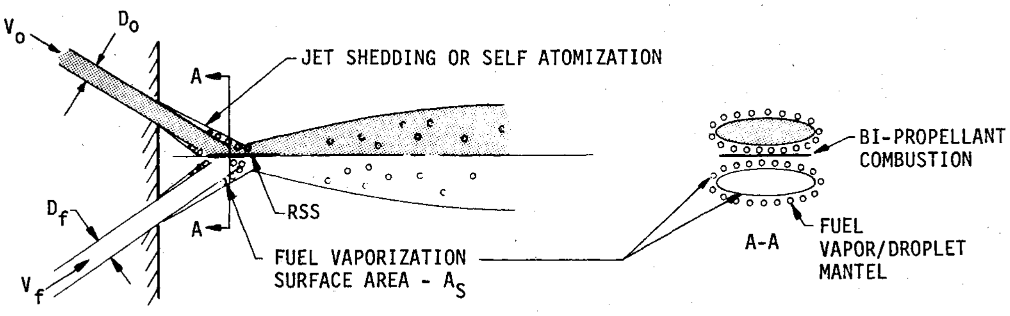

Fig. 7 Fuel vaporization controlled RSS model.

Reynolds number for a given jet. Given this Reynolds number dependent fuel vaporization surface area, the following relationships should apply for coherent stream injectors:

$$W_{V_{\text{critical}}} \propto A_S f\,(Re_F{}^{1/2})\,P_{c_{\text{critical}}} \tag{3}$$

$$P_{c_{\text{critical}}} \propto A_S{}^{-1}\,Re_F{}^{-1/2} \tag{4}$$

$$A_S \propto Re_F \tag{5}$$

$$P_{c_{\text{critical}}} \propto Re_F{}^{-3/2} \tag{6}$$

Preatomization of the fuel with atomized spray fan impingement injectors generates increased preimpingement fuel vaporization surfaces in relation to the coherent stream injector. Hence, the preimpingement fuel vaporization surface area of the atomized spray impingement element is not expected to be as sensitive to changes in Reynold number. If it can be assumed to be insensitive for a given element, the following relationship should apply for atomized spray impingement:

$$A_S \neq f\,(Re_F) \tag{7}$$

$$P_{c_{\text{critical}}} \propto Re_F{}^{-1/2} \tag{8}$$

Therefore, the critical chamber pressure for coherent streams is expected to be more dependent on Reynolds number than the atomized spray impingement injector elements.

The model shows good agreement with the coherent stream element data in that the measured exponent on Re_F is equal to $-3/2$. The exponent on Re_F is found to be -0.24 rather than -0.5 for the atomized spray elements. The agreement with the experimental data is sufficient to conclude that RSS is controlled primarily by fuel vaporization rate-limited combustion.

RSS Injector Design Criteria

The RSS design criteria specified herein are applicable to the N_2O_4 oxidizer and amine fuels propellant combinations. The criteria are limited to injector elements with fuel orifice diameters of 0.030 in. or less. The following design and operating ranges are applicable:

Chamber pressure	80–1000 psia
Fuel velocity	25–200 ft/s
Oxidizer velocity	25–150 ft/s
Fuel temperature	50–300°F
Oxidizer temperature	50–160°F
Mixture ratio	1.4–2.0

These criteria deal only with the optimization of the element mixing processes. Other criteria required to achieve high performance, stability, and compatibility are not included.

Criteria 1: RSS should be avoided to maximize performance.

Solution: Select element size and velocity that will permit operation within the mix regimes defined by Figs. 5 and 6.

Criteria 2: Transitions from mixed to separated regimes within the engine operating envelope should be avoided.

Solution: Select elements that will remain within either the mixed or separated regimes defined by Figs. 5 and 6.

Criteria 3: If operation within the separated regime cannot be avoided, then interelement mixing should be maximized to minimize RSS effects.

Solution: Orient elements within the injector pattern to provide interspray mixing, taking into account the effect of RSS on the element mixing.

Conclusions

Injector design criteria for coping with RSS has been developed using high-speed color photography.[21] Data correlations made on the basis of a fuel vaporization controlled combustion RSS model show that regimes of RSS are correlated for both coherent stream and atomized spray injector elements. The model independent variables are chamber pressure and the fuel orifice Reynolds number. The chamber pressure exhibits the strongest influence on RSS. Increasing chamber pressure promotes RSS. Orifice diameter, injection velocity, and propellant temperature effects are correlated with the fuel orifice Reynolds number. Increasing any one of these promotes RSS.

Acknowledgments

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