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Solid-Fuel Ramjet Fuel Regression Rate/Thrust Modulation

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An experimental investigation was conducted to determine if inlet air swirl and/or secondary gaseous injection could be used effectively for fuel regression rate control or thrust modulation in a solid-fuel ramjet. Inlet swirl characteristics were measured in nonreacting flows. Tests were conducted at high and low air mass fluxes using three fuel compositions with equivalence ratios between 0.5 and 1.8. Swirl introduced downstream of the air inlet was found to be effective for obtaining limited increases in the fuel regression rate, but the magnitude was highly dependent upon motor geometry. Swirl interactions with the reattaching inlet flow and/or significantly increased near-wall mixing were found to be detrimental to efficient combustion. Energetic gaseous fuels (H_2, C_2H_4) can be easily injected and efficiently burned under fuel-lean conditions to significantly enhance thrust.

Nomenclature

A = area
D = fuel port diameter
d = inlet diameter
F = thrust
f = fuel-to-air ratio
G = mass flux, m/A_p
G = w_{mo}/u_{mo}
G_x = flux of axial momentum
G_θ = axial flux of swirl momentum
h = convective heat transfer coefficient
L_G = fuel grain length
m = mass flow rate
P = pressure
q = heat transfer rate
Re = Reynolds number
r = fuel regression rate
S = swirl number
S_{avg} = w/u
T = temperature
u = axial velocity
u = mass averaged u
w = tangential (swirl) velocity
w = mass averaged w
η = temperature-rise combustion efficiency based on P_c
ϕ = equivalence ratio, f/f_{st}

Subscripts
air = air
c = combustion chamber
i = air inlet
inj = injected
mo = maximum value at air inlet
P = fuel port
st = stoichiometric
th = theoretical value
x = axial component
θ = tangential component

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Introduction

FOR medium- to long-range tactical missiles the solid-fuel ramjet (SFRJ) offers advantages of design simplicity and lower life-cycle costs than liquid-fueled ramjets. In addition, recent advances in metallized fuel compositions[1,2] have resulted in combustion efficiencies as high as those obtained in liquid-fueled systems together with high-density impulse.

One continuing disadvantage of the solid-fuel ramjet has been its limited operating envelope with high combustion efficiency and thrust. For example, if it is designed for peak performance at high altitude and Mach number it generally would have marginal thrust at takeover from boost, which would occur at lower altitude and Mach number.

This behavior is a direct result of the manner in which fuel is provided to the combustion process in the solid-fuel ramjet. Nonmetallized fuels generally have average burning rates that vary approximately as the square root of the air mass flux through the fuel port. The burning rate also depends upon the inlet air temperature (i.e., altitude and Mach number) and, to a lesser extent, on operating pressure and combustor geometry.[1,3] In addition, the combustion efficiency of nonmetallized/all-hydrocarbon fuels generally is a minimum at an equivalence ratio of unity and increases almost linearly as the fuel/air ratio is decreased. Some metallized fuels seem to have combustion efficiencies much less sensitive to equivalence ratio, but they generally will not burn at the low pressures that occur at very high altitudes.[4]

These behavior characteristics make the solid-fuel ramjet self-throttling, but not to the extent needed to provide adequate fuel flow rate and/or combustion efficiency over wide altitude/Mach number envelopes. Techniques are required to provide wider control of the fuel regression rate and/or thrust while maintaining high combustion efficiency. Bypass designs are often desired in order to increase fuel loading and can also improve combustion efficiency. Variable bypass is one means of providing increased control of fuel regression rate. However, combustion efficiency may vary significantly (at least for hydrocarbon fuels) with the amount of bypass air, offsetting some of the benefits of the changing regression rate. In addition, a valve must be used in the inlet air ducting, adding system complexity and possible flow coupling between the combustor and bypass duct. The latter could lead to undesirable flow/pressure oscillations.

Other techniques are needed to provide increased control of fuel regression rate and/or thrust. One possible alternative technique is the use of variable swirl at the air inlet. This technique is often used in liquid ramjet and gas turbine combustors to enhance combustion efficiency.[5] Although it would increase system complexity somewhat, it may provide adequate regression rate control without the undesirable coupling that may occur in variable bypass systems. However, it is not known how the combustion efficiency is effected by the presence of swirl in the solid fuel ramjet. In addition, if the swirl momentum is not dissipated before passing through the exhaust nozzle, axial thrust can be reduced. Another possibility for modulating the thrust and/or regression rate of an SFRJ is the use of secondary injection of air, oxygen, gaseous fuel, or combustion catalysts into one or more locations within the inlet or combustor. This latter technique could have the advantage of providing increased combustion efficiency if soot oxidation could be enhanced.

In this experimental investigation, inlet air swirl and secondary gaseous injection were investigated to determine their effects on fuel regression rate and combustion efficiency. Polymethylmethacrylate (PMM) and hydroxy-terminated polybutadiene (HTPB) fuels were utilized with inlet air temperatures to 694 K and with inlet air swirl vane angles to 45 deg. Grain length was varied to help separate the effects of swirl and equivalence ratio on the combustion efficiency. N_2O, NO, O_2, air, C_2H_4, and H_2 were examined as combustion enhancers under fuel-rich and fuel-lean conditions. Head-end, midgrain, and aft-mixing chamber locations were employed to help distinguish the locations in which the combustion process could be modified.

Description of Apparatus and Test Procedures

Ramjet Motor

The ramjet motor used in this investigation has been used in earlier investigations.[6] Inlet air from the plenum dumps was turned 90 deg by a wedge in the head-end. An igniter torch flame was injected through a radially oriented port at the face of the air inlet step for ignition of the motor (Fig. 1). During the ignition process ethylene gas was also injected either upstream of the air inlet or through a single radially oriented port within the recirculation region.

Secondary Gaseous Injection

Secondary injection was examined at three locations through the fuel grain wall: in the recirculation zone (flameholder area); just downstream of flow reattachment; and further downstream within the region of the developing boundary layer (in which is located a turbulent diffusion flame). In addition, gaseous injection through the inlet step face, into the inlet plenum, and into the aft mixing chamber were examined.

PMM was used in the initial test series and had a nominal length of 30.5 cm and an internal diameter of 3.8 cm. A sudden expansion inlet was used which provided an inlet step height of 1.27 cm (A_p/A_i = 9.0).

Flow reattachment normally occurs between 7 and 8 step heights (in the present geometry, 8.5–10 cm from the air inlet step). Thus, the three fuel-grain injection locations chosen were 5.1, 12.7, and 20.3 cm from the air inlet face. The 30.5 cm fuel grains were then cut into two segments with lengths of 5.1 and 25.4 cm, 12.7 and 17.8 cm, or 20.3 and 10.2 cm. An injection ring was designed (Fig. 2) to provide radial injection through eight equally spaced, 1.6-mm-diam holes.

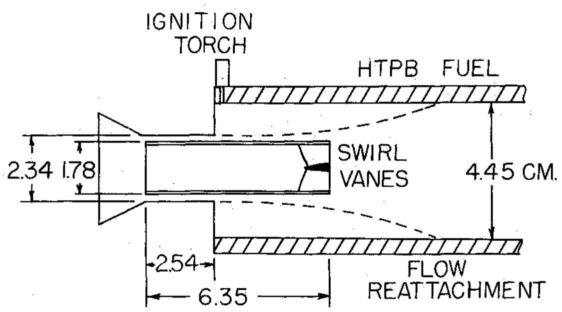

Fig. 1 Schematic of the tube-in-hole injector with swirl vanes.

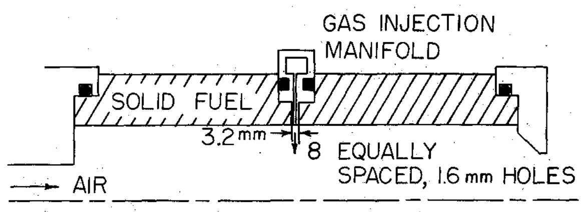

Fig. 2 Schematic of the secondary gas injection system.

This required a metal spacer of 3.2 mm width to be located between the two fuel segments (Fig. 2). Fuel wall injection velocity varied between approximately 9 and 46 m/s as the injection mass flow rate was increased from 1% to 5% of the inlet air flow. A nominal one-dimensional port velocity was approximately 90 m/s.

Gaseous injection was also used through the inlet step face. The injection was provided through eight equally spaced 1.2-mm-diameter holes. For an injection gas mass flow rate equal to 1% of the inlet air flow rate the injection velocity was approximately 20 m/s.

In a second test series, both PMM and HTPB were used in which grain length and port diameter were varied to control equivalence ratio and flammability limits.

Inlet Air Swirl

In the initial tests to determine the sensitivity of regression rate to swirl, a modified tube-in-hole injector (Fig. 1) was used with only a small amount of swirl. Approximately 43% of the air flow passed through the outer annulus to maintain the recirculation region/flameholder. The other 57% of the air flow was passed through a central swirl element that extended 3.81 cm into the combustor. Introducing swirl into the entire inlet air flow prohibits ignition, apparently from a destruction of the fuel-rich recirculation zone that normally acts as the flameholder.[7] In addition, if the swirl was introduced using a tube-in-hole injector that did not extend sufficiently into the fuel port, the same result was obtained. In the initial tests, the swirl was induced by machining six flutes with a twist of one turn in 12.7 cm. The latter resulted in an inlet swirl angle of approximately 5 deg to the motor centerline.

Following the initial tests, which showed considerable regression rate sensitivity to swirl, a new set of inlet swirl devices were fabricated and a series of nonreacting flow measurements were made to characterize better the flow before conducting motor firings. Each swirl blade was a cambered airfoil. Tubes with 15-, 30-, and 45-deg (from the axial centerline) swirl vane elements and a tube without a swirler were used.

A hemispherical, three-hole stagnation pressure probe was used to measure flow velocities at the exit plane of the tube-in-hole injector. The probe was mounted on a vernier translation stand to allow for movement across the flow. The probe could be translated on its own axis as well as rotated.

The pressure readings and the angles at which the maximum values occurred were used to calculate axial and tangential velocity components (assuming that the net radial component was equal to zero).

The introduction of swirl into a dump combustor both complicates the flow pattern and causes difficulty in characterization of the flowfield. The upstream recirculation zone behavior and the turbulence intensities are affected by the downstream swirl.[8,9] In addition, flow angles are usually less than blade angles and the flow blockage also affects both the pressure drop through the swirlers and the downstream flow.[10] When only a portion of the inlet flow passes through the swirl vanes (as in the tube-in-hole injector required for the SFRJ), increased blockage with increased vane angles also results in a lower percentage of the total flow being swirled.

The nondimensionalized swirl number S is one way to characterize the inlet flow. Following the work of Lilley[8]:

$$S = G_\theta/[G_x(d/2)] \tag{1}$$

Making the same assumptions as Lilley of solid body rotation (a flat upstream axial velocity profile, and an increasing swirl velocity from 0 at the hub to w_{mo} at the outer edge), the analysis results in

$$S = \{(G/2) / [1 - (G/2)^2]\} \tag{2}$$

In another attempt to characterize the swirl in the present apparatus, the mass averaged tangential velocity

$$w = \Sigma m \; w / \Sigma m \tag{3}$$

and the mass averaged axial velocity

$$u = \Sigma m \; u / \Sigma m \tag{4}$$

were calculated. w/u was calculated and denoted S_{avg}.

Following the cold-flow characterization of the inlet flow, a series of hot firings were conducted using PMM, HTPB, and 18818 (an HTPB-based fuel) fuels with various fuel port diameters and lengths.

Results and Discussion

Secondary Gaseous Injection

Initial Test Series Using PMM

A series of screening tests of short duration were conducted to determine the sensitivity of fuel regression rate to the various injected gas compositions, flow rates, and injection locations. These tests were for 6 s, 3 s without injection, and 3 s with injection; just long enough for steady-state conditions to be attained. The results of these screening tests were used to select the conditions to be used for longer duration tests in which performance would be measured. The rise in chamber pressure expected from the increased mass flow alone was compared to the measured value. If the injected gas behaves as an inert substance it would only affect the combustion pressure through changes in the total mass flow rate, gas properties, and temperature at the entrance to the exhaust nozzle. Changes in gas properties had a negligible effect. A typical combustor temperature was 2200 K and the injected gas temperature was approximately 280 K. For no changes in the combustion efficiency resulting from the injected gas, the expected $\Delta P_c/P_c$ for choked exhaust nozzle flow would then be approximately as shown by the solid line in Fig. 3.

The data in Fig. 3 show that air injected through the fuel grain surface aft of flow reattachment did not enhance the combustion. The injected air was quite cold (approximately 280 K) and, therefore, could have had a quenching effect on the boundary-layer combustion. Use of "in-flight" high-temperature air should be examined in the future. Small amounts

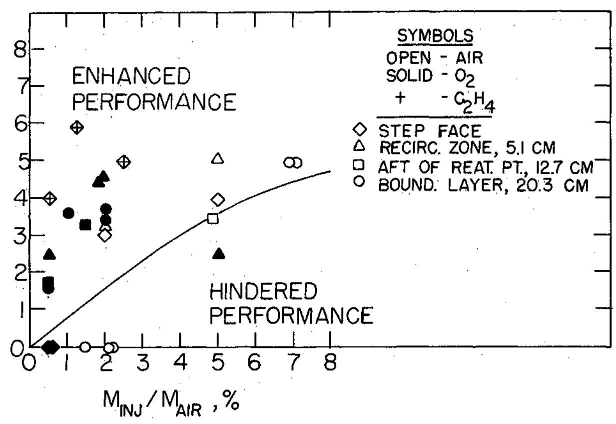

Fig. 3 Effects of secondary gas injection on operating pressure using PMM fuel.

of air injected into the fuel-rich recirculation zone seemed to provide small improvements.

Unheated oxygen injection resulted in significant enhancement of combustion pressure, especially when introduced into the recirculation zone in small amounts. The average fuel/air ratio is found from the fuel mass loss during a test of known duration and the measured air flow rate. These tests were conducted with a fuel/air ratio of approximately 0.09 (ϕ = 0.75). Small amounts of oxygen injection into any of the fuel-rich regions seems to enhance combustion. It seems that high flow rates of oxygen penetrated the fuel-rich region without time for enhanced chemical reactions. Based upon these screening test results, two additional tests were conducted with test times of approximately 30 s. These tests were made to examine the effects of 1% oxygen injection into the recirculation region (through the fuel-grain wall) and had a total grain length of 35.5 cm; 5 cm of PMM, then the injection ring, and then 30.5 cm of PMM.

The recirculation region is fuel rich.[11] In addition, early work with grains that contained small amounts of oxidizer operated without step-inlet flameholders.[12] Thus, increasing the oxygen level within the recirculation zone can be expected to reduce the required inlet step height. As anticipated, low flow rates [in the short (6 s) duration tests (Fig. 3)] enhanced combustion. The longer burn time results (Table 1) showed a decrease in combustion efficiency. Although the "nominal" and "1% O_2 Recirculation Zone" tests used different grain lengths, PMM generally has a combustion efficiency that is insensitive to equivalence ratio for nonbypass configurations.[13] As the fuel regressed, the injection ring progressively protruded more from the fuel surface, providing increased near-wall mixing with burn time, with an apparent adverse effect on combustion.

The need for further testing was evident, especially using HTPB, but at this point it was apparent that fuel wall injection of small amounts of air or oxygen was not a viable method for providing fuel mass flow rate control using the injection ring technique, because no significant change in regression rate was achieved and combustion efficiency was not enhanced.

The data from the screening tests with step-face injection are also presented in Fig. 3. Unheated air provided only small gains in combustion pressure. Oxygen injection resulted in increased flame luminosity in the recirculation zone, but apparently did not affect downstream combustion significantly (the overall equivalence ratio was approximately 0.7). Injection of ethylene resulted in significant increases in combustion pressure, as was expected for the lean fuel/air ratio without injection.

A full-duration test (Table 1) was conducted using 1% of ethylene with an injection velocity of approximately 20 m/s. Near-wall velocities (reverse flow) are of the order of 0.03 of the inlet air velocity,[4] or approximately 5 m/s in the present configuration. Thus, the injected ethylene probably penetrated the recirculation zone and passed into the shear layer and core air flow. Comparison of the results with those for no injection showed no significant effect on the fuel regression

Table 1 Summary of experimental data from initial test series using PMM fuel

Condition	Nominal	1% C_2H_4 face injection	1% O_2 recirculation zone	inlet air swirl
L_g, cm	30.3	30.1	35.5	29.9
m_{air}, kg/s	0.092	0.092	0.092	0.092
T_{air}, inlet, K	303	299	278	280
r, mm/s	0.158	0.160	0.161	0.180
ϕ	0.69	0.70	0.82	0.79
P_c, $N/m^2 \times 10^{-6}$	0.382	0.407	0.398	0.385
T_{th}, K	1888	2176	2076	2034
η	83	82	79	86

rate or combustion efficiency. However, the increased chamber pressure resulting from the efficient burning of the ethylene with the core air provided increased thrust.

Second Test Series Using PMM and HTPB

As a result of the negligible effects of secondary gaseous injection on fuel regression rate observed in the initial test series, a second series of tests was conducted to examine the possibility of thrust modulation through changes in combustion characteristics introduced by the injected gases.

Tests were conducted with both PMM and HTPB fuels at various equivalence ratios. A plot of the measured changes in chamber pressure obtained with secondary gas injection, compared to the expected changes in pressure for equilibrium adiabatic combustion is given in Fig. 4. The equilibrium adiabatic values for gas properties and combustion temperature were calculated using the measured chamber pressure. These values change insignificantly for small (1 atm) changes in pressure. The combustion pressures (for 100% efficiency) with and without gaseous injection were then calculated assuming one-dimensional, isentropic, fixed property flow through the exhaust nozzle. The equilibrium adiabatic values for $\Delta P_c/P_c$ were thus determined. If the combustion efficiency was less than 100% in the actual test, then the measured P_c values were less than used to calculate the above ratio. If η did not change with injection, then the measured $\Delta P_c/P_c$ would remain practically unchanged from the $\eta = 100\%$ theoretical value. If, however, the secondary gas injection increased η, then the measured value of $\Delta P_c/P_c$ would be greater than for the $\eta = 100\%$ theoretical value.

For H_2 injection into the head-end there was a significant increase in P_c (and thrust), with the strongest effect occurring for $\phi < 1.0$. In order to verify the expected dependence on ϕ, one firing was conducted with $\phi > 1.0$, which resulted in little change in P_c. However, there was a visible increase in soot exiting from the motor, indicating that the hydrogen was replacing the carbon in the combustion process. The hydrogen injection apparently increased the overall combustion efficiency.

N_2O and/or NO have received attention in liquid hydrocarbon combustion as possible enhancers/catalysts for soot combustion. For N_2O injection at the head-end and inlet step with PMM fuel, the increase in P_c was greater than that expected from equilibrium combustion, indicating some possible enhanced conversion of C/CO. However, this enhancement did not seem to vary with equivalence ratio and there was no evidence of enhancement with HTPB fuel. HTPB generally produces significantly more soot than PMM, indicating that enhanced soot consumption was not occurring to any major degree.

For NO injection with HTPB fuel, the increase in P_c was less than expected from equilibrium combustion, indicating no beneficial effect on the soot present.

In summary, secondary injection of H_2 (or C_2H_4) into the SFRJ generally results in at least the expected equilibrium-adiabatic increase in pressure/thrust. This could be a viable method for augmenting thrust of the SFRJ at critical points in the operating envelope (such as takeover from boost), allowing the motor design to be tailored to provide higher performance over the balance of the operating envelope. N_2O and NO did not appear to provide any significant enhancement for soot combustion.

Inlet Air Swirl

Initial Screening Tests Using PMM Fuel

Only one test was conducted in the initial screening tests using inlet air swirl (Table 1). Approximately 43% of the air was injected axially to maintain the recirculation zone flameholding ability. This could be reduced to perhaps only 10%–20%, resulting in more air with swirl. The amount of swirl was also intentionally kept small (5 deg from the axial direction) to determine if regression rate was sensitive to the swirl.

The small amount of swirl increased the fuel regression rate by 14%. This resulted in an increase in equivalence ratio from 0.69 to 0.79. Some nonuniformity in regression rate was also evident.

Screening Tests Using 18818 Fuel

A series of initial hot runs was completed to test the integrity of the tube-in-hole injector design. During this phase it was found that the initially designed tubes, which extended 0.64 cm beyond the aft end of the inlet, did not allow ignition of the motor. It was suspected that the swirling flow was interfering with the recirculation zone, disrupting the flame stabilization area. The tubes were lengthened so that the swirl dump was 3.81 cm beyond the inlet step (Fig. 1), which solved the problem. This length was considerably less than the reattachment length of approximately 7 cm. This detrimental effect of upstream swirl on the recirculation region was in agreement with the results of Jones[7] and Duesterhaus and Högl.[14]

Cold Flow Measurements

A summary of the results from the cold flow studies is given in Table 2. There was an increase in the difference between the maximum and mass averaged axial velocities from 9% for no swirl, to 77% for 45-deg swirl vanes. The same was true for the difference between the maximum and mass averaged tangential velocities, with 27% difference at 15 deg and 77% difference at 45 deg. With no swirl vanes present, the center tube passed 70% of the airflow. With 15-deg and 30-deg vane angles the center tube passed only 56% and 46%, respectively. Thus, as the vane angle increased to increase the swirl velocity the increased blockage actually reduced the mass of swirled air. The blockage effect also caused the velocities between the tube and inlet wall to increase as the vane angle increased. The swirl number, as calculated by Eq. (2) (based on solid-body rotation), increased with vane angle to 30 deg and then decreased. The mass averaged velocity ratio (Eq. (3) divided by Eq. (4)) increased continually with vane angle.

Initial Tests Using 18818 Fuel

The initial 18818 tests were conducted with a fixed combustor geometry: $L_G = 30.5$ cm, $D = 4.45$ cm, $d = 2.34$ cm, motor exhaust nozzle throat diameter = 2.4 cm, with a tube-in-hole injector of 6.35 cm length; with 3.81 cm in the fuel port. The test conditions were also approximately constant with an air-only preheat time of 6 s, ignition time of 0.8 s, burn time of 6 s, purge time of 4 s, and an inlet air temperature between 613 and 628 K. These test conditions resulted in a nominal chamber pressure of 7.14 atm and a very fuel-rich condition with equivalence ratios between 1.5 and 1.8. Without swirl the fuel grain regression rate increased in the axial direction from the inlet plane to a point approximately 5 cm downstream. Thereafter, the regression rate was approximately constant. The grains used with the 15-deg swirl vanes showed the same characteristics. However, four areas that corresponded with the four vanes of the swirl element exhibited slightly indented regions extending from 5 cm beyond the step to 10 cm, slowly blending into a concentric surface. Therefore, the swirl was transmitted into the shear layer and affected the reattachment region flow. The 30-deg test grains showed a marked increase in the indented regions, and they extended to 13 cm beyond the step. The 45-deg test grains were even more pronounced in the indented region, but not

Table 2 Cold flow results for inlet air swirl

Blade angle	(deg)	0	15	30	45
u (max)	(m/s)	145	188	231	250
w (max)	(m/s)	0	94	159	160
$\bar{u}$	(m/s)	132	155	171	141
u (outer flow)	(m/s)	117	120	153	180
$\bar{w}$	(m/s)	0	74	105	90
S_{avg}		0	0.478	0.616	0.640
S		0	0.335	0.649	0.544

Table 3 Results from swirl tests

Run #	Vane angle, deg	m, kg/s	T_i, K	P_c, MPa	F, N	r, mm/s	ϕ	η
HTPB-1	0	0.293	624	0.807	391	0.574	0.751	98.5
-2	0	0.308	615	0.848	405	0.597	0.754	94.7
-3	15	0.312	631	0.883	423	0.633	0.788	98.3
-4	15	0.289	639	0.848	396	0.622	0.847	102.8
-5	15	0.289	626	0.841	405	0.612	0.730	104.2
-6	30	0.303	638	0.834	396	0.638	0.821	90.5
-7	30	0.318	613	0.862	414	0.635	0.691	92.7
-8	0	0.603	659	0.738	738	0.655	0.671	89.5
-9	15	0.613	643	0.758	752	0.678	0.681	93.3
PMM-1	0	0.184	566	0.703	218	0.251	0.632	99.1
-2	0	0.242	573	0.952	302	0.287	0.617	96.7
-3	0	0.327	647	0.862	423	0.361	0.685	94.2
-4	15	0.180	551	0.669	200	0.226	0.583	91.1
-5	15	0.246	581	0.986	316	0.300	0.659	96.9
-6	15	0.335	654	0.917	449	0.384	0.687	101.0

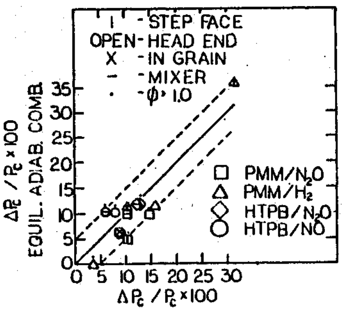

Fig. 4 Measured vs calculated rise in combustion pressure with secondary gaseous injection.

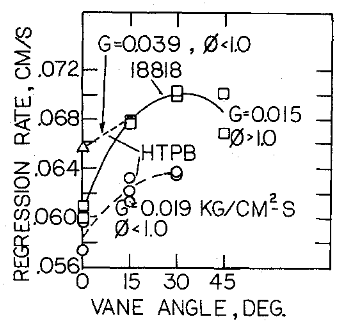

Fig. 5 Regression rate vs inlet swirl vane angle, T_{air} = 611–337 K.

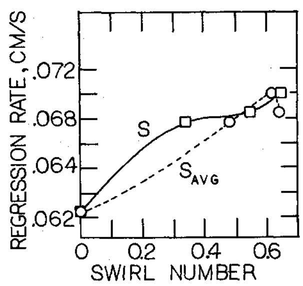

Fig. 6 Regression rate vs swirl number for 18818 fuel, T_{air} = 613–628 K, $\phi > 1.0$.

as elongated. The angles of the indented regions corresponded to the respective swirl vane angles.

A plot of the regression rate versus swirl vane angle is given in Fig. 5, and vs S and S_{avg} in Fig. 6. The average (based on weight loss) regression rate for the fuel grain increased rapidly for small amounts (15-deg vane angle) of swirl. Further increases in swirl vane angles (or swirl number) had much less effect on regression rate; the result of the reduced mass of swirled air as vane angle was increased. The swirl number correlated reasonably well with regression rate. S_{avg} seemed to be in question for the 45-deg vanes, perhaps caused by the large amount of flow blockage.

The increased values of fuel regression rate that were obtained using swirl may be of limited utility. For example, variable bypass geometries can also be used to control the fuel regression rate. A typical value of G in a SFRJ is 0.042 kg/cm²s without bypass. Fifty percent bypass would then yield a fuel port G of 0.021. Because r varies approximately as $G^{0.4}$, a 50% reduction in G would result in an approximately 25% reduction in r. In comparison, 30-deg swirl vanes, in the present configuration, would yield only about one-half of this effect on r. These results using 18818 fuel were also in agreement with the results of Duesterhaus and Högl.[14]

Test Series Using PMM and HTPB with $\phi < 1.0$

Tests were conducted using HTPB fuel with high G (0.039 kg/cm²s) and low G (0.019), and PMM fuel with low G (0.014). For the low-G cases, a 2.34-cm-diam inlet with a tube-in-hole injector with either no vanes or swirl vane angles of 15 or 30 deg was used. For the high-G cases, a 2.86-cm-diameter inlet with a tube-in-hole injector with either no vanes or swirl vanes angles of 15 deg was used. This larger inlet was necessary because of excessive blockage with the smaller inlet, resulting in the flow being choked through the inlet during the hot firing.

For this series of tests, the fuel grains were sized to give an equivalence ratio between approximately 0.6 and 0.8, in contrast to the fuel-rich environment of the initial tests.

Results are presented in Table 3. A plot of the regression rate versus swirl vane angle for HTPB fuel is given in Fig. 5, together with the earlier results obtained using 18818 in a fuel-rich environment. The effect of swirl on the average regression rate was influenced primarily by the length of the fuel grain (equivalence ratio) and the fraction of the total inlet air that was given a swirl velocity. Higher values of G resulted in higher fuel regression rates, as expected.

For the HTPB fuel, the effects of swirl at low G were similar to those conducted with 18818. The regression rate increased slightly with 15-deg vanes, but increasing the vane angle to 30 deg had little effect because the increased vane blockage reduced the mass flow that had a swirl component. The tests conducted with fuel-rich 18818 conditions showed more of an increase in regression rate with swirl. This difference was caused by the higher equivalence ratios (longer grain lengths). The swirl effects on r occur primarily downstream of flow reattachment because the tube-in-hole injector was used to prevent the swirl from destroying the flame holding action of the step inlet. At high G there was little effect on r with 15 deg of swirl. Only approximately 30% of the airflow passed through the swirl element because of the larger inlet diameter, resulting in much less swirl in the flow adjacent to the fuel surface.

There was no consistent trend of combustion efficiency with swirl, although small amounts of swirl (15-deg vane angle) did seem to result in improved efficiency. The effects of swirl on η can be quite complex. Increased swirl results in increased ϕ, which for HTPB results in decreased η. However, small increases in mixing near the wall can improve η (through better mixing of the fuel-rich flow below the flame zone with the core air) and high mixing rates can destroy or greatly broaden the flame zone structure and reduce η.

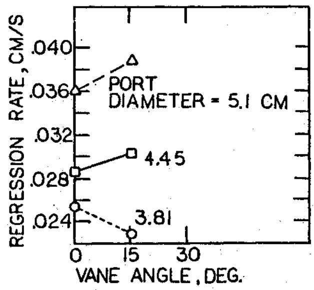

Fig. 7 Regression rate vs inlet swirl vane angle for PMM fuel, T_{air} = 583 K, G = 0.014 kg/cm²s, $\phi < 1.0$.

The results obtained for PMM fuel are presented in Table 3 and Fig. 7. It is observed from Fig. 7 that with the smallest port diameter of 3.81 cm, swirl decreased the average fuel regression rate. Apparently, the smaller port diameter permitted the swirled flow to spread to the wall very near or in the flow reattachment zone. This would greatly increase the near-wall mixing and result in a broader flame zone and less heat flux to the fuel wall. For the larger port diameters the regression rate increased with 15-deg swirl vanes by approximately the same percentage as for HTPB with equivalent port diameters. Another observed result is that increasing A_p/A_i with fixed G increases the average fuel regression rate for no inlet swirl. For grains in which the recirculation zone is only a small part of the overall grain length, boundary-layer heat transfer dominates the average fuel regression rate. For PMM and $\phi < 1.0$, radiation heat transfer to the wall is small because very little soot is present. Thus, convective heat transfer dominates the fuel regression rate. The convective heat transfer coefficient can be estimated from the Nusselt number for turbulent flow, which in turn varies as the Reynolds number to the 0.8 power.

$$r \sim q \sim h \sim Re^{0.8}/D \sim G^{0.8}D^{0.8}/D \sim G^{0.8}/D^{0.2}$$

For fixed G, the fuel regression rate would decrease as D increased. This boundary-layer behavior is opposite to that observed in Fig. 7. The tube-in-hole injector together with the large recirculation zone lengths (caused by the large step heights) significantly change the average heat flux to the wall from that expected for turbulent boundary-layer behavior.

The swirl velocity introduced at the combustor inlet, if maintained through the exhaust nozzle, would result in a significant reduction in axial thrust from that expected, based upon one-dimensional flow. This did not occur, indicating that the swirl velocity component was dissipated in the aft mixing chamber.

These results indicate that swirl can be used to increase somewhat the fuel regression rate. However, the observed wide variation in the effects of swirl with combustor and inlet geometry and operating conditions indicate that it will not be a simply applied method for regression rate control.

Conclusions

Small amounts of oxygen-rich gases can be injected into the fuel-rich recirculation zone to reduce the required inlet step height, without significantly affecting the average fuel regression rate. High secondary gaseous injection rates/velocities of oxidizer seem to penetrate the fuel-rich zones too rapidly to enhance combustion. In addition, high mixing rates introduced near the fuel grain surface can reduce combustion efficiency, apparently the result of a broadening of the flame zone. Energetic gaseous fuels (H_2, C_2H_4) can be injected easily and efficiently burned under fuel-lean conditions to significantly enhance thrust, permitting better optimization of the combustor design for wide operating envelope requirements.

Inlet air swirl can be used to obtain limited increases in fuel regression rate, but the obtainable change is significantly less than obtainable with variable bypass air and results in nonuniform regression in the upstream portion of the fuel grain. In the solid fuel ramjet, swirl must be introduced downstream of the inlet step and an outer annulus of unswirled air must be used in order not to disrupt the flame stabilizing recirculation flow region. In addition, if the swirl strongly interacts with the reattachment flow it may result in too much mixing and a reduction in fuel regression rate. With the tube-in-hole injectors required to introduce inlet swirl in the SFRJ, increased swirl increases blockage and, therefore, reduces the percentage of the inlet mass flow that is given tangential momentum. For HTPB-based fuels, the average fuel regression rate increased with swirl number (for the centrally swirled flow) to a maximum of 16% with $S = 0.6$. However, because of the increased blockage, the magnitude of the change in regression rate with changes in swirl vane angle decreased with increasing vane angle. The primary effects of swirl on regression rate occur downstream of flow reattachment and, therefore, it is more effective with long grains for which $\phi > 1.0$. The effects of swirl on regression rate were found to depend primarily upon grain and inlet geometry and operating conditions. Although it may be useful for providing some thrust modulation for the SFRJ, it will not be simply applied to existing designs that do not incorporate inlet swirl.

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