Regression and Combustion Characteristics of Boron Containing Fuels for Solid Fuel Ramjets

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A windowed, two-dimensional solid-fuel-ramjet motor was used with high-speed motion picture cameras to study the effects of fuel composition, pressure, and air mass flux on the surface behavior of metallized fuels within both the recirculation and boundary-layer combustion regions. Surface behavior and near-surface combustion characteristics were examined to help explain the regression rate/performance characteristics observed in actual motor hardware. Fuels containing no combustion catalyst exhibited the characteristic of extending the combustion envelope to lower pressures with lower values of Shore A hardness. Ignition/flammability limits appeared to be a strong function of surface pyrolysis within the recirculation region. Most metallized fuels exhibited shedding of flakes of (unburned) material from the fuel surface. Flake thickness for boron fuels was typically 200 μ, independent of pressure, and surface areas varied from less than 1 mm^2 to approximately 22 mm^2. The mass losses attributable to the flaking process play a major role in the overall fuel mass loss mechanism. Bimetallic fuels and fuels containing a combustion catalyst apparently had surface reactions which increase the surface temperature. This should be beneficial for obtaining more complete combustion of the metals within the motor.

Introduction

FLAME stabilization in solid-fuel-ramjet (SFRJ) combustors is generally provided by a rearward facing step at the air inlet. The step creates a recirculation zone into which oxygen is transported from across the turbulent shear layer. Fuel is provided from the wall, sweeping upstream and up the step face and then downstream along the inside of the shear layer.[1] A flame is observed to initiate along the shear layer, just downstream of the step face. The flame propagates along the shear layer, spreading significantly in width before it contacts the fuel surface at the reattachment point. The recirculation zone is often fuel rich and has a length of 7–8 inlet step heights.[2–4] Downstream of an unsteady reattachment of the inlet flow, a turbulent boundary layer develops along the fuel grain. Within this boundary layer, a diffusion flame zone is formed. Fuel is transported from the fuel surface, and oxygen diffuses from the core airflow. The flame transports heat to the fuel surface both by convection and radiation. Flammability/ignition limits are usually specified in terms of the port-to-inlet area ratio or the inlet step height to port diameter ratio.[3–5] The required ratio depends primarily upon the air inlet temperature, the port-to-throat area ratio, and the fuel composition.

When significant amounts of metal are added to the solid fuel, the combustion characteristics can be greatly altered.[6] There is much less binder material to generate gaseous fuel for the diffusion flame, resulting in a flame that is closer to the fuel surface. The peculiar characteristics of metal particle ignition and combustion have been studied using well-controlled experimental systems. Boron particles, in particular, were found very difficult to ignite and to sustain combustion,[7–11] due to a molten oxide layer formed around the particle, serving as a barrier between the boron and the oxidizing gases. Temperatures as high as 1900 K are necessary to evaporate this oxide layer and to facilitate the conditions for ignition. In the SFRJ combustor, metallic material leaving the fuel surface must be heated to ignition temperature by the time it passes through the diffusion flame and reaches the oxygen rich core airflow. Thus, particle size, surface ejection velocity and direction, and surface temperature will all influence the combustion characteristics of the metal, the regression rate of the fuel, and the performance of the ramjet motor.[12]

Metallized fuel screening tests in axisymmetric motors have shown that small changes in composition and/or manufacturing methods can significantly change the obtainable regression rates and/or performance. It is expected that these changes are directly related to the behavior of the metallic particles in the surface and near-surface regions. Recently,[13] metallized fuels have also been evaluated using strand burners, and that study has shown the importance of the near-surface combustion in determining regression rate without crossflow. Convective effects may significantly increase the sensitivity of regression rate to the behavior of the metallic particles.

In this investigation a windowed, two-dimensional SFRJ motor was used with high-speed motion picture cameras to study the effects of fuel composition, pressure, and air mass flux on the surface behavior of metallized fuels within both the recirculation and boundary-layer combustion regions. The objective was to determine if observed surface behavior and near-surface combustion characteristics could be used to help explain the regression rate and/or performance characteristics observed in actual motor hardware.

Description of Apparatus

The two-dimensional SFRJ motor is shown in Fig. 1. The head-end included a motor-driven inlet step, which could be used to change the step height from run to run or during a run. The combustor was 6.35 cm wide with a 2.54 cm height between the fuel slabs, which were located on the top and

Received May 22, 1989; revision received Dec. 5, 1989.

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bottom surfaces of the combustor. The fuel slabs were 40.6 cm long and 0.64 cm thick and were bonded to the walls. Two air-purged viewing windows were utilized, one within the recirculation region (3.8 cm aft of the inlet) and one near the aft end of the fuel slab (34.3 cm aft of the inlet), in the boundary-layer combustion region. Black Plexiglas was often bonded to the side walls in order to reduce heat losses and to improve ignition/flammability limits for the two-dimensional configuration. Because no inlet steps were present on the side walls, very little erosion of the Plexiglas occurred during a run. One set of side plates was used for many tests. For a specified flow rate, combustion pressure (P_c) was controlled by changing the throat area of the graphite exhaust nozzle.

A methane-fueled vitiated air heater was utilized to provide the desired inlet air temperatures (T_{air}). Oxygen makeup was provided downstream of the heater. The air heater was acoustically isolated from the motor with a sonic choke.

Two Hycam high-speed motion picture cameras were used. Most of the films were taken at 6000 pictures/s. The viewing area was through a 1.27 cm diam window.

A data acquisition/control system was used to control all gas flow rates and test times and to record and reduce all flow rate, pressure, and gas temperature data.

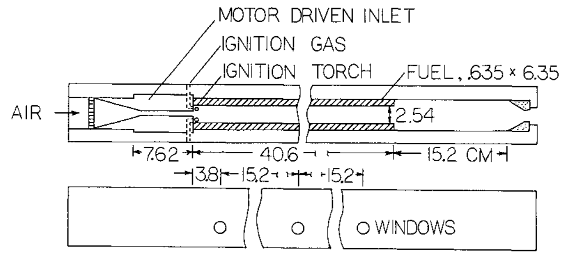

Fig. 1 Schematic of the two-dimensional solid fuel ramjet.

Method of Investigation

The investigation was divided into two test series. The first series was conducted to obtain general characteristics and differences (required ignition/sustain pressures, etc.) between a wide variety of metallized fuel compositions. These fuels were provided by the Chemical Systems Division, United Technologies, the Atlantic Research Corporation, and the Naval Weapons Center. Only limited quantities of fuel were available, requiring that the motor not be loaded entirely with metallized fuel. A summary of the fuels and test conditions

Table 1 Fuels and conditions for test series 1[a]

Fuel composition	Fuel number	Configuration	Shore A hardness	G, gm/cm^2 s
Ti/2B-1	1-1	Zecorez–top: 2.54 cm width Zecorez, 3.8 cm Metal—bottom	20	14/35
Ti/2B-2	1-2		26	
Ti/2B/cat/Mg	1-3		45	
Ti/2B/AlB_{12}/cat/Mg	1-4		58	
Ti/2B/catalyst	1-5		55	
B/Mg	1-6	Zecorez—top Metal—bottom	62	35
B/catalyst	1-7		70	14/35
[b]B_4C/Mg	1-8		72	35
[b]B_4C + 5%/Mg − 5%	1-9		75	
B_4C + 20%/Mg − 15%	1-10		74	

[a]P_c was varied between 0.28 and 1.38 MPa (40 and 200 psia); T_{air} was varied between 555 and 667 K (1000 and 1200 R); step-to-port height ratio h/H was 0.25 except as noted.
[b]$h/H = 0.325$.

Table 2 Fuels and conditions for test series 2

Fuel composition	Fuel number	Configuration
B_4C/Mg/catalyst/Zr/binder	2-1	Zecorez or HTPB—top; 2.54–3.8 cm Zecorez or HTPB—bottom, 3.8–2.54 cm metal—bottom
+10%/−10%/− −/− −/− −	2-2	
+15%/−20%/− −/− −/+5%	2-3	
− −/−2%/− −/+2%/− −	2-4	
− −/−5%/− −/+5%/− −	2-5	
+15%/−30%/+5%/− −/+10%	2-6	
+5%/−20%/+5%/− −/+10%	2-7	
+15%/−35%/+10%/− −/+10%	2-8	
B/catalyst	2-9/1-7	
+10%/−25%/+5%/− −/+10%	2-10	Metal—top and bottom
+10%/−25%/+5%/− −/+10%	2-11	
+15%/−30%/+5%/− −/+10%	2-12	

$h/H = 0.325$.
$P_c = 0.39$–1.27 MPa (57–185 psia).
$T_{air} = 552$–685 K (993–1234 R).
$G = 14$ g/cm^2 s (0.2 lbm/in.^{2} s).
HTPB = Hydroxy-terminated polybutadiene.

for the first test series is presented in Table 1. Bimetallics and various additives were evaluated for their effectiveness in providing enhanced heating and ignition of the metallic particles.

In the second test series, the fuel compositions were varied more systematically than in the first series. Filming and window purge techniques were also improved, allowing more quantitative data to be obtained on the surface and near-surface behavior. A summary of the series 2 test conditions is presented in Table 2. The compositions are given as changes from those of the initial fuel (Number 2-1).

Most tests were conducted using both high-speed motion picture cameras simultaneously so that both regions of combustion could be observed for identical test conditions.

Results and Discussion

Series 1 Test Results

As discussed above, the first test series was conducted to obtain general combustion characteristics and differences between the various fuel compositions and combustion enhancers. In Fig. 2 the approximate minimum pressure for sustained combustion (after termination of igniter) is plotted against the Shore A hardness for the fuel. It is observed that the minimum pressures required for sustained combustion increased with Shore A hardness, except for the two formulations which contained a combustion catalyst. These data are for an air mass flux (G) of 35 gm/cm^2 s (based on the port cross-sectional area) and $h/H = 0.25$ (with corresponding initial port Mach number of approximately 0.2). This trend may result from the fact that higher Shore A hardness often indicates either a higher content of metal or a harder and less volatile polymeric matrix, both of which could lead to difficulties in achieving ignition and sustained combustion. At the lower G of 14 gm/cm^2 s, where the metallized fuels do not generally burn as well, this trend was not present. In addition, increasing h/H to 0.325 caused most fuels to sustain combustion. The reason for this correlation with fuel hardness is not directly apparent. The heats of vaporization and the products of surface decomposition need to be determined to see if either can be correlated with the hardness of the materials. However, in Ref. 14 it was reported that removal of carbon black from HTPB fuels significantly increased the required h/H for sustained combustion. Also, the fuels that contained a combustion catalyst were observed to produce significant amounts of surface reaction and generally had better combustion limits than fuels without a catalyst. Both of these results indicate that the ignition/flammability limits are a strong function of the surface pyrolysis processes within the recirculation region. This observation implies that one fuel type could possibly be used in the recirculation region to obtain the best ignition/flammability limits and another, higher performance fuel that has more severe inlet step height requirements could then possibly be used downstream.

The films indicated several characteristics that were typical of all fuel compositions. One of these was that all of the fuels exhibited shedding of flakes of material from the fuel surface. The quantity and size varied with composition. Figures 3 and 4 show examples of these flakes in the recirculation and boundary-layer combustion regions, respectively. For fuels containing metals other than boron or boron compounds, the gas phase contained many high-velocity burning particles of varying sizes from approximately 10-μ (limits of resolution) to several hundreds of microns (see Fig. 4). Boron particles were generally not observed, apparently because they were smaller than the approximately 10-μ resolution limit of the films.

Several other qualitative characteristics which were observed are as follows.

1) Fuels containing a combustion catalyst generally had better ignition/flammability characteristics.

2) Metallized fuels did not burn well in the two-dimensional motor when pressure was less than 0.28 MPa (40 psia).

3) At low values of G (14 g/cm^2 s), metallized fuels do not burn as well as at higher values of G. There were larger surface agglomerates, more shedding of surface layers of material, and larger particles within the gas phase.

4) The bimetallic fuels such as Ti/2B showed evidence of surface reactions. A green-yellow glow was observed below many of the larger surface flakes which were not yet exposed to the oxygen in the core air.

5) Under higher G conditions, fuels containing catalyst/Mg had molten, glowing material on the surface, also indicating the presence of surface reactions.

Surface reactions can provide the advantage of heating the metallic material before it leaves the surface. Thus, less time would be required to heat the particles to ignition temperatures. This should result in more complete burning of the metal within the motor and higher performance.

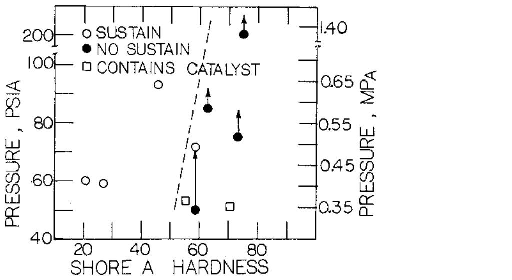

Fig. 2 Effect of Shore A hardness on two-dimensional motor sustain pressure for metallized fuels: $h/H = 0.25$, $G = 35$ g/cm^{2}s.

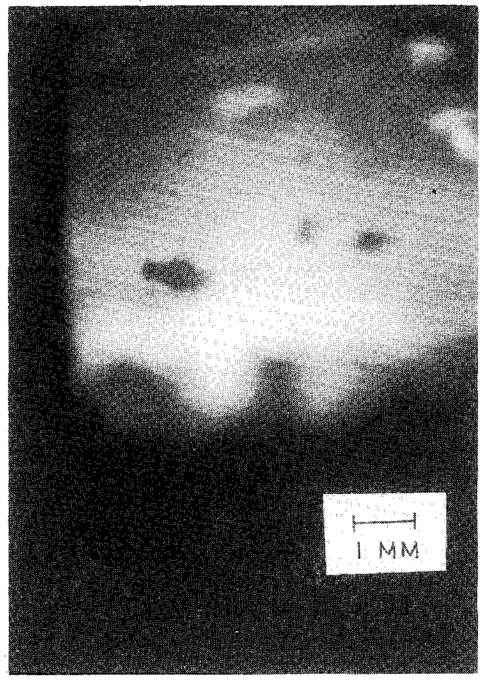

Fig. 3 Surface flakes and magnesium surface agglomerate: fuel 2-2, recirculation zone, $P_c = 1.05$ MPa, $G = 14.8$ g/cm^{2}s.

Series 2 Test Results

The second test series resulted in both new qualitative observations and quantitative data on the behavior of the surface flaking as a function of pressure, air mass flux, and location within the combustor.

Table 3 presents some ignition/flammability results in terms of required pressures. The "air-only" (pre-ignition) pressures are given together with the pressures that resulted after ignition. Observed sustain and no-sustain conditions are reported.

No attempt was made to accurately determine the ignition/flammability limits. The data resulted from attempts to burn

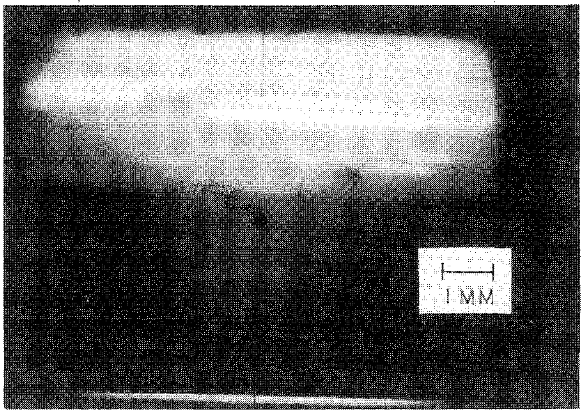

Fig. 4 Surface flakes and magnesium particles in gas phase: fuel 2-3, boundary-layer region, $P_c = 0.96$ MPa, $G = 14$ g/cm²s.

the fuels under several preselected throat diameter conditions. Nevertheless, a few qualitative observations could be obtained from the data. The addition of small amounts of zirconium or large increases in the B_4C content in place of Mg had only small effects on the combustion limits. Flammability limits may also be affected by the air inlet temperature and not only by the pressure. However, there was no consistent trend observed over the limited range of temperatures that were used.

Some additional observations from the films were as follows:

1) Unignited small flakes of surface material were shed by all fuels.

2) B_4C produced very small particles in the gas phase, as did boron.

3) Magnesium produced very large particles in the gas phase.

4) Fuels containing a combustion catalyst had significantly greater numbers of hot, unignited particles on the fuel surface.

The following discussions are concerned with the quantitative data that were obtained from the high-speed motion pictures. In particular, details were obtained on the surface-layer flaking and its relative role in the overall fuel mass loss mechanism. In addition, data on the shapes of the flakes and their behavior, size, and velocity distributions were obtained. The films also provided information on the effects of different operating parameters, such as pressure and fuel composition, as well as the influence of the axial location in the combustion chamber (reattachment vs boundary-layer zones) on the above mentioned processes.

Generally, it was observed that a significant portion of the condensed combustible material (i.e., burning and nonburning material particles or agglomerates and pieces and flakes of the condensed fuel) moving in the gas flow originated at the location of the reattachment and within the adjacent recirculation zone.

Qualitatively, it was observed that, in the reattachment-recirculation zone, larger flakes were generated at much higher rates than in the boundary-layer region. The flaking phenomenon was particularly noticeable in metallized fuels which contained the combustion catalyst. These fuels exhibited very intense, bright combustion occupying the entire gas volume. With the typical spatial resolution in the motion pictures of approximately 10 μ, no metal particles or agglomerates could be seen in the gas stream, indicating that if (boron) particles did exist, they were very small. Nevertheless, upon ejection from the condensed surface, the flakes were relatively large (typically a few millimeters across) and seemed to be nonburning, whereas in the recirculation zone they initially moved with the circulating gas in the upstream direction and close to the surface. They then turned downstream, moving at a larger distance from the surface, and apparently broke up near the interface with the shear layer. The movement in the recirculation zone provides the residence time for heating up and possibly for ignition.

The boron fuels which incorporated a catalyst typically contained high loadings of boron or boron compounds. Observations indicated that the flakes coming off of the surface were very thin compared to their other dimensions, with an almost uniform thickness of 200 μ. Hence, the flake surface area could also represent its volume or mass.

The size, shape, trajectory, and velocity of the flakes were obtained by a frame-by-frame analysis of the high-speed motion pictures. Typically, each flake could be observed in a number of successive pictures, avoiding the possibility of completely obscuring another flake in the field of view along the line of sight.

Figure 5 presents the flake number and area distributions obtained within the recirculation zone for a boron/catalyst fuel at a chamber pressure of 0.65 MPa (95 psia) and an air mass flux of 14.8 g/cm² s (0.21 lbm/in.² s). Figure 6 shows the

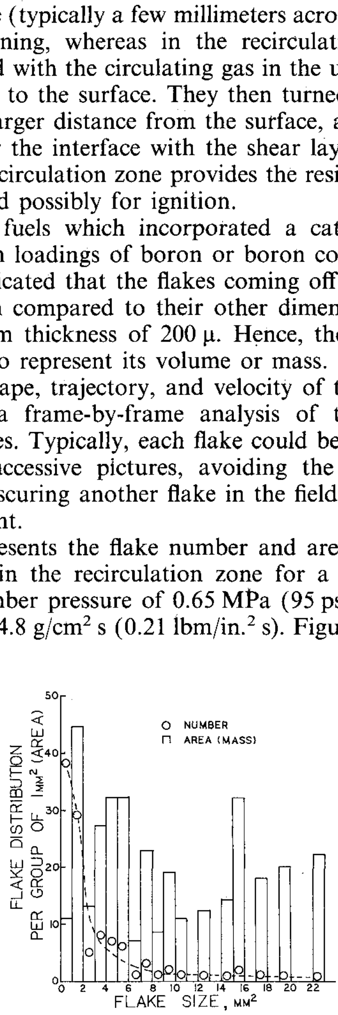

Fig. 5 Flake number and area (mass) distributions: fuel 2-9, $P_c = 0.65$ MPa, $G = 14.8$ g/cm²s, recirculation zone.

Table 3 Ignition/flammability limits

Fuel Number	No sustain, P_{air}/P_{ign}, MPa		Sustain, P_{air}/P_c, MPa	
2-1	——	——	0.36/0.51	0.37/0.58
2-2	——	——	0.28/0.52	0.54/1.03
2-3	0.22/0.45	0.32/0.49	0.43/0.96	0.63/1.26
2-4	0.30/0.55	0.31/0.46	0.30/0.69	——
2-5	0.23/0.48	——	0.35/0.59	0.50/1.02
2-6	0.25/0.41	0.31/0.53	0.50/1.08	——
2-7	0.25/0.39	——	0.52/1.05	——
2-8	0.20/0.45	0.35/0.57	0.48/1.02	——
2-9	0.19/0.43	——	0.34/0.65	0.48/1.03

$h/H = 0.325$.
$G = 14$ g/cm² s (0.2 lbm/in.² s).

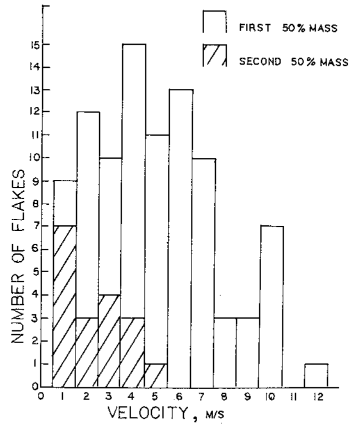

Fig. 6 Flake velocity distributions: fuel 2-9, $P_c = 0.65$ MPa, $G = 14.8$ g/cm^{2}s, recirculation zone.

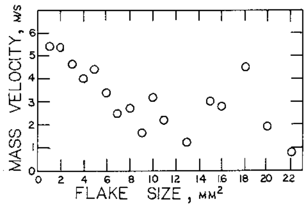

Fig. 7 Flake velocity vs size: fuel 2-9, $P_c = 0.65$ MPa, $G = 14.8$ g/cm^{2}s, recirculation zone.

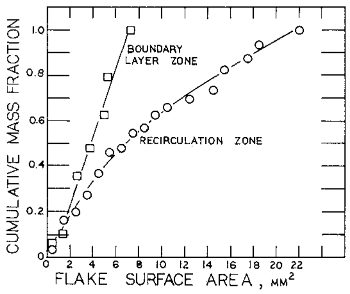

Fig. 8 Cumulative mass fraction vs surface area: fuel 2-9, $P_c = 0.65$ MPa, $G = 14.8$ g/cm^{2}s.

flake velocity distribution while they were moving in the field of view.

As has already been mentioned, almost all of the flakes in the recirculation zone at short distances from the surface (up to about 5 mm) moved in the upstream direction. Figure 6 demonstrates that the smaller flakes (first 50% of mass) had higher velocities (average velocity of approximately 4.5 m/s) than the larger (second 50% of mass) flakes (average velocity of approximately 2.4 m/s). The overall average velocity of the flakes was 3.7 m/s. This velocity was much lower than the incoming air velocity of approximately 150 m/s. In general, the smaller the particles, the larger their typical velocity (see Fig. 7), which could be expected based on drag forces.

Results similar to those presented above were obtained for all test conditions and served as the basis for studying the influence of different operating parameters. Typically about 100–150 particles/flakes were used for the calculations of the different distributions in each of the cases investigated.

Boundary-Layer Region vs Recirculation Zone Behavior

The cumulative flake mass (area) distributions from both regions are presented in Fig. 8 for the above fuel and test conditions. Note that the 50% cumulative flake-area point for the recirculation region was at a much larger size than for the boundary-layer region (6.5 vs 3.8 mm^2, respectively). These correspond to flake masses of approximately 2 and 1.1 mg and volumes of about 1.3 and 0.76 mm^3, respectively. In addition, the rate of flake ejection was much higher in the reattachment-recirculation zone than in the boundary-layer region. The mass loss rates attributed to the flaking phenomenon corresponded to relatively high fuel regression rates: approximately 1.7 and 0.34 mm/s, respectively. These values are of the order of the local regression rates. Hence, one can conclude that for the boron/catalyst fuels, the flaking phenomenon plays a major role in the overall fuel mass loss mechanism. Most flakes and particles in the boundary-layer region moved relatively close to the fuel surface (within about 3 mm). The velocities in the boundary-layer region were about one order of magnitude higher than in the recirculation zone (typically 30–40 m/s).

Effect of Chamber Pressure

The effect of pressure on the flaking process was studied using the same boron/catalyst fuel and air mass flux (14.8 g/cm^2 s) as discussed above, but at a higher pressure of

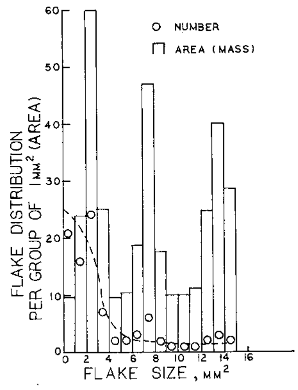

Fig. 9 Flake number and area (mass) distributions: fuel 2-9, $P_c = 1.03$ MPa, $G = 14.8$ g/cm^{2}s.

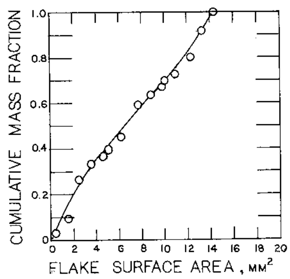

Fig. 10 Cumulative mass fraction vs surface area: fuel 2-9, $P_c = 1.03$ MPa, $G = 14.8$ g/cm^{2}s, recirculation zone.

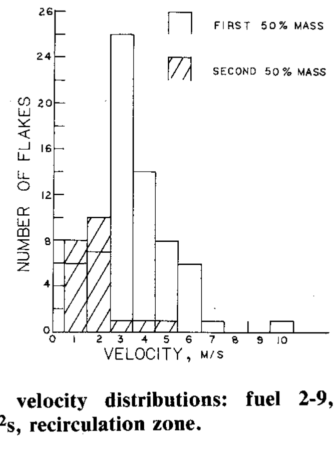

Fig. 11 Flake velocity distributions: fuel 2-9, $P_c = 1.03$ MPa, $G = 14.8$ g/cm^{2}s, recirculation zone.

1.03 MPa (vs 0.65 MPa). The flake thickness of approximately 200 μ was not affected by pressure.

Figure 9 shows the flake number and area (i.e., volume or mass) distributions for the reattachment-recirculation zone at the higher pressure. The cumulative mass (area) fraction behavior, shown in Fig. 10, indicated that there was little effect of pressure on flake size. The 50% point in Fig. 10 (pressure of 1.03 MPa) is at a flake area of 6.5 mm^2, exactly equal to the value in Fig. 8 for 0.65 MPa.

The flake velocities at high pressure, however, were lower than at low pressures. Figure 11 gives the velocity distributions of the first and second 50% flake masses for a pressure of 1.03 MPa. Note again, that the larger 50% flake group had much lower flake velocities (1.9 m/s average) than the smaller 50% flake group (3.5 m/s average). The average velocity for all flakes was 2.7 m/s at 1.03 MPa compared to 3.7 m/s at 0.65 MPa. It was roughly a similar fraction of the inlet air velocity (which, of course, decreased with increasing pressure) for the two cases.

Effect of Fuel Composition

The fuel composition, and possibly the manufacturing process, were observed to affect the surface material ejection phenomena. A fuel consisting of B_4C with catalyst was compared to the former boron fuel with the same catalyst at the same pressure of 1.03 MPa and air mass flux of 14.8 g/cm^2 s. Data were obtained from the reattachment-recirculation region.

The appearance of the flames were very similar, i.e., no individual burning particles were observed, and the flame had the appearance of a gas phase combustion process. The flakes ejected from the surface of the B_4C fuel were thicker, but had smaller volume (mass). Figure 12 presents the number and volume distributions for the ejected material. Figure 13 shows the cumulative volume fraction vs the ejected flake volume. The 50% cumulative volume point was at a particle volume of 0.078 mm^3 (compared to 1.3 mm^3 for the boron fuel). This is equivalent to the volume of a sphere of 0.53 mm diam compared to an equivalent diameter of 1.35 mm for the B/catalyst fuel. The flake velocity distribution exhibited a higher velocity range with an average of about 6 m/s (compared to 2.7 m/s), which can be attributed to the smaller particles.

Evaluation of Flake Residence Time in the Recirculation Zone

Typically, a flake ejected into the gas stream in the recirculation zone first moved relatively close to the wall in the upstream direction. It then turned to the downstream direction, gaining velocity, and joined the freestream outside of the recirculation zone. The velocities associated with the upstream motion were much lower than for the downstream direction. Thus, the residence time of the flakes in the recirculation zone could be estimated on the basis of the reattachment distance divided by the mean flake velocity.

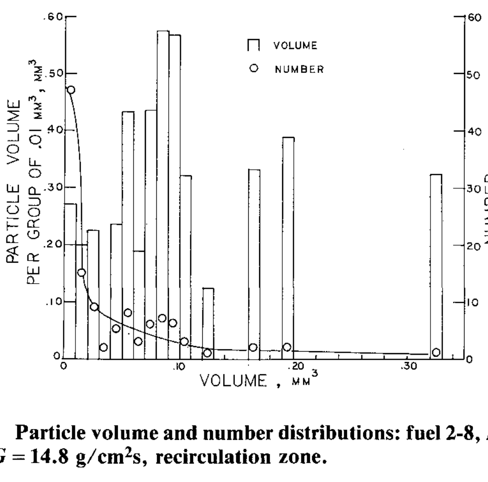

Fig. 12 Particle volume and number distributions: fuel 2-8, $P_c = 1.02$ MPa, $G = 14.8$ g/cm^{2}s, recirculation zone.

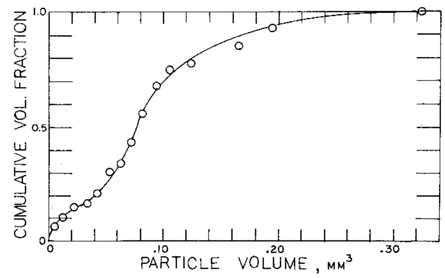

Fig. 13 Cumulative volume fraction: fuel 2-8, $P_c = 1.02$ MPa, $G = 14.8$ g/cm^{2}s, recirculation zone.

In the present tests, the reattachment distance was approximately 50 mm. With typical flake velocities ranging between 2 and 7 m/s, the residence times of the flakes in the recirculation zone were in the range of 7–25 ms.

Conclusions

Major conclusions and findings from this investigation include the following.

1) Fuels containing no combustion catalyst tested at a nominal air mass flux of 35 gm/cm^2 s exhibited the characteristic of extending the combustion envelope to lower pressures with lower values of Shore A hardness. Previous observed effects of carbon black and the observed surface reactions with bimetallic fuels indicated that ignition/flammability limits are a strong function of surface pyrolysis processes within the recirculation region. Multi-compositioned fuel grains may prove beneficial for obtaining the best combination of ignition/flammability limits and motor performance.

2) Most metallized fuels exhibited shedding of flakes of (unburned) material from the fuel surface. Flake thickness for boron fuels was typically 200 μ, independent of pressure, and surface areas varied from less than 1 mm^2 to approximately 22 mm^2.

3) The mass losses attributable to the flaking process play a major role in the overall fuel mass loss mechanism.

4) The flakes were much larger and were ejected more often within the recirculation region (where flake residence times were from 7 to 25 ms) than in the boundary-layer region. In the latter region the flakes remained close to the surface and had much higher velocities.

5) Boron and boron-carbide fuels produced very small ($<$10–20 μ) particles in the gas phase; whereas magnesium produced various particle sizes, including particles with diameters into the hundreds of microns.

6) Fuels containing a combustion catalyst generally had better ignition/flammability characteristics.

7) Bimetallic fuels and fuels containing a combustion catalyst apparently have surface reactions that increase the surface temperature. This should be beneficial for obtaining more complete combustion of the metals within the motor.

8) Metallized fuels burn better at higher pressures ($>$0.28 MPa in the two-dimensional motor) and higher values of the air mass flux.

Acknowledgment

This investigation was supported by the Naval Weapons Center, China Lake, California under work request N60530-87-WR-30009 and the Naval Postgraduate School.

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