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Technical Notes

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Ignition and Flammability Characteristics of Solid Fuel Ramjets

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Nomenclature

A_i = inlet area
A_p = fuel grain port area
A_t = nozzle throat area
D = fuel grain port diameter
G = air mass flux
H = inlet step height
P_c = chamber pressure
T_i = inlet air temperature

Introduction

FLAME stabilization in solid fuel ramjets is often provided using a rearward facing step at the grain inlet.[1-3] This step inlet arrangement results in the formation of three distinct combustion zones. The products and reactants are rapidly mixed in the recirculation zone which forms immediately aft of the rearward facing step. It is desirable from both pressure loss and fuel loading standpoints that the minimum step height which is capable of sustaining combustion be used. The flow reattachment zone generally occurs at a distance between six and eight step heights.[4-6] However, it moves toward the step inlet with wall mass addition at a constant inlet mass flux. The leading edge of the reattachment zone is quasi-stationary with a fixed inlet step height, regardless of variations in inlet step velocity, provided that the flow remains turbulent. Downstream of the flow reattachment zone, along most of the fuel grain length, a gas-phase diffusion flame is formed within the highly turbulent boundary layer which develops over the condensed fuel surface.

In order to achieve ignition, a stable, high-temperature recirculation zone is required. The rearward-facing step height must be large enough to form the required recirculation zone for a given gas velocity in the combustion chamber and a given fuel composition. There are three major parameters that affect the ignition limits for a fuel of given composition: A_p/A_i (or H/D), A_p/A_{th} and T_i. Increasing values provide better ignition and flammability characteristics.

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In many combustion systems flammability limits are wider than ignition limits. This may also be the situation in the Solid Fuel Ramjet Motor (SFRJ) since after ignition is established, the entire fuel surface is providing hot fuel vapor to the combustion process. If this is the case, then perhaps the inlet step size can be reduced after ignition, or alternate flame-holding geometries/devices can be employed.

In this investigation, the ignition and flammability characteristics of several types of fuel compositions were studied under various operating conditions and inlet geometries using a windowed, two-dimensional motor.

Description of Apparatus

The two-dimensional SFRJ (Fig. 1) incorporated a variable inlet step height, driven by a variable-speed, reversible, high-torque ac motor which could position the step during SFRJ operation. Two viewing windows were used, near the reattachment point and just prior to the aft mixing chamber where the boundary layer was more developed. Nominal test conditions were G = 13.7–14.3 gm/cm^2 sec, T_i = 510–533 K, and P_c = 8.7–9.5 atm.

Vitiated air with oxygen make-up was used to provide the required air inlet temperatures. Most high-speed motion pictures were taken at 6000 pps. Two cameras were used. Each camera had a timing light source which was used to determine film speed. Another external timing light provided pulses for cross-reference to the step height and chamber pressure on the computer based data acquisition system.

Results and Discussion

Motor Operation

In order to minimize the possibility of any transient effects, the step travel rate was set to 0.9 mm/sec or a net step rate of 0.48 mm/sec after correcting for an average fuel regression rate of 0.41 mm/sec. A rate any slower than this sometimes resulted in the flammability limit not being reached during the allotted 5 sec burn time. Significantly faster rates would not permit steady-state operation to result if the step motion was terminated.

Continuous fuel slabs were not available during the initial runs. The uneven joints in the fuel slabs downstream of the inlet step sometimes contributed to the formation of a second "step." This step would serve as a flameholder after the decreasing inlet step had reached the flammability limits of the fuel. Combustion would continue in the aft section of the

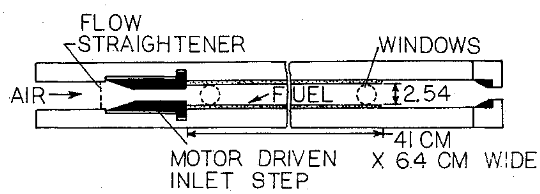

Fig. 1 Schematic of two-dimensional solid fuel ramjet motor with motor-driven inlet step.

Table 1 Summary of *H/D* results

FUEL	Ignition limit	SFRJ flameout
R45HT + DDI + Carbon Black (ref.)	.165–.177	.143
95% Ref, 5% CE1,* no carbon black	.175–.183	—
95% Ref, 5% CE1	.146–.155	.129–.135
90% Ref, 10% CE1	.145–.148	.130–.146
95% Ref, 5% CE2	.150–.157	—
45% Ref, 50% Zecorez, 5% IDP	.187–.193	.145–.152
34% Ref, 60% Zecorez, 6% IDP	.160–.169	.152–.155

*Combustor enhancer.

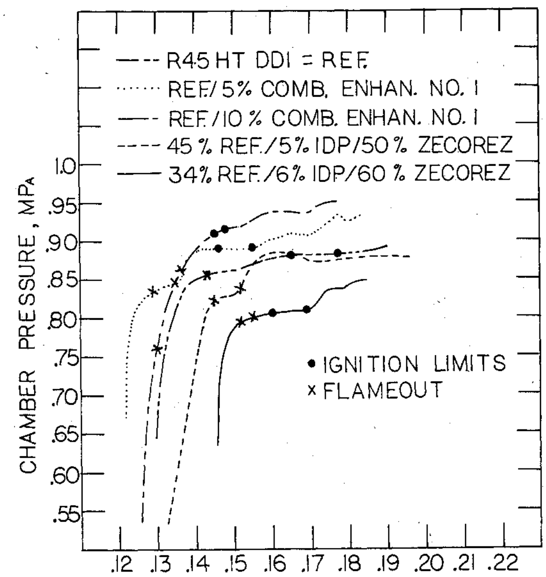

Fig. 2 Ignition and flammability limits in the two-dimensional motor.

combustion chamber. This use of smaller recirculation zones within the high-temperature, fuel-rich boundary layer region could possibly be used to reduce port-to-injector area ratio requirements at some expense in nonuniform fuel regression.

Fuel Characteristics

All the fuels displayed similar ignition and flameout characteristics (Fig. 2). The SFRJ was usually ignited very close to the ignition limits of the given fuel. As the step height was initially decreased, the chamber pressure would generally decrease. The exhaust flame could be seen to diminish in intensity during reduction in step height. During SFRJ operation with the inlet step at a fixed position, a bright and stable flame could be observed just aft of the recirculation zone and in the boundary layer region. The flames were initially steady as the step height was decreased and then the flame near the reattachment zone would begin to extinguish and re-ignite in a oscillatory manner. The size and intensity of the oscillatory flame would decrease until it disappeared altogether, which indicated flameout of the recirculation zone. A small pressure drop generally occurred with the beginning of the oscillatory flame in the recirculation zone. The pressure drop rate would then increase and remain fairly constant as the flameout effects from the recirculation zone proceeded aft through the boundary layer region. The films from the boundary layer camera indicated that flameout in this region did not coincide with the recirculation zone flameout, but rather consistently occurred approximately 0.35 to 0.50 s later. Flameout in this region occurred rather abruptly without the slow decay observed in the other region. While the *H/D* data for various fuels (see Table 1) indicated SFRJ flameout limits lower than the ignition limits, the actual flammability limits were reached when the recirculation zone flamed out during the first pressure drop, close to the ignition limits. It should be noted that these *H/D* limits are for the two-dimensional motor and are not directly applicable to axisymmetric geometries.

At lower operating pressures a more distinct difference between the ignition and flammability limits may be observed. Flameout along the fuel surface occurred at a rate between 60 and 90 cm/s, between one and two orders of magnitude less than the average port velocity. The velocities were on the order of the maximum laminar flame speeds (premixed) for hydrocarbons in air. Typically, HTPB-based fuels have surface decomposition products with molecular weights between heptane (C_7H_{16}) and nonane (C_9H_{20}).[7] Longer flameout times were observed for the fuels with a combustion enhancer, where the oxidizer enriched surface regions reduced the rate of chamber pressure decrease and increased fuel resistance to flame blowoff.

The fuels which contained the most enhancer (5% and 10%), together with carbon black, displayed the lowest ignition/flammability limits, or smallest step height requirements (Table 1). However, the fuel with 5% enhancer, but without carbon black, had among the largest step requirements. It can be seen that the presence of carbon black improved the ignition/flammability limits more than the addition of 5% combustion enhancer. The fuel containing 50% Zecorez exhibited a somewhat different characteristic, showing an initial constant pressure followed by a pressure rise before the pressure decayed. It should be noted that, although the differences in required step heights varied only 30% from fuel to fuel, the results of the tests were very repeatable.

The inclusion of carbon black in the fuel results in the radiative heat transfer from the flame being absorbed at the surface, rather than also providing subsurface heating. Not only are subsurface properties (strength) improved but, apparently, so are the products of surface pyrolysis which depend upon the surface temperature. Strahle et al.[8] have shown analytically that flame stabilization in the SFRJ may be very dependent on small changes in the blowing rate. In addition, the current results with and without carbon black indicate that flame stabilization may also be very sensitive to the fuel species/kinetics of the near-wall combustion process. Thus, small changes in fuel composition can be expected to result in different required A_p/A_i ratios.

Before the ignition limit is reached, decreasing step height resulted in a decrease in motor pressure for some fuels. This behavior may also prove beneficial for providing some thrust modulation/control for the SFRJ. In the present 2-D motor, a typical reduction of 9% in *H/D* resulted in an approximately 3.5% reduction in fuel regression rate (assuming HTPB with an equivalence ratio of 0.8). For cylindrical grains this effect can be expected to be significantly greater. For example, Gany and Netzer[6] found the sensitivity of burning rate to *H/D* to be approximately two to three times greater in a miniature SFRJ motor. The problem of providing thrust modulation by varying inlet step height/geometry is, however, not so simple. For HTPB type fuels the combustion efficiency increases as the equivalence ratio decreases below unity, negating some of the thrust modulation obtainable by decreasing the fuel regression rate at fixed air flowrate.

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