Fuel-Rich Particle-Laden Plume Combustion

Klaus Schadow*
Naval Weapons Center, China Lake, Calif.

Theme

IN ducted rockets using boron-loaded solid propellants, primary chamber reaction products containing unreacted gaseous and particulate fuels mix, ignite, and burn with a subsonic airstream in a secondary chamber. It is generally known that the overall efficiency of these systems decreases with decreasing secondary chamber pressure, increasing air-to-fuel ratio, and decreasing propellant mass flow. Based on systematic tests in a subscale rocket motor,[1,2] it was determined that ignition of the gaseous fuel components of the primary chamber with the airstream is critical if high combustion efficiency of the boron components is to be achieved. This study provides additional insight into the ignition and combustion processes of the gaseous components with and without boron particles. It will be shown that reduction of the primary exhaust velocity to subsonic speed significantly improves the ignition process of the gaseous components and the boron particle combustion efficiency.

Contents

The investigation consisted of 3 phases: a) a study of the ignition process of the gaseous components without boron particles as a function of primary chamber temperature (T_{CP}), primary exhaust velocity (v_{EX-P}), secondary chamber air-only pressure (p_{RS}), air-to-fuel ratio (a/f), and enhanced mixing rate through mixing devices, b) an investigation of the influence of boron and inert aluminum oxide particles on the ignition process of the gaseous components, and c) measurement of the combustion efficiency of boron-loaded solid propellants.

For the study of the gaseous components without boron particles a fuel-rich solid propellant with 55% ammonium perchlorate (AP) and 45% carboxyl-terminated polybutadiene (CTPB) was used in the primary motor. Various amounts of oxygen were added to change the primary chamber exhaust temperature. The v_{EX-P} was varied independently of the solid propellant mass flow by using a nozzle with a constant throat at the end of the solid propellant motor (D_{TM}) and a second nozzle with a variable throat at the end of the primary motor blast tube (D_{TP}) (Fig. 1). Figure 1 shows the strong influence of the primary v_{EX-P} on the ignition of the gaseous components, as indicated by the secondary chamber temperatures and the position of the flame onset which was observed through quartz windows. Under the specific test conditions indicated in Fig. 1 and at $T_{CP} \sim 1900$K the gaseous components did not ignite at supersonic v_{EX-P}(1.7 Mach). At low supersonic flow ($v_{EX-P} = 1.15$ Mach) the gaseous components ignited 10 cm downstream from the primary nozzle, and the combustion temperatures were below 1500 K. With subsonic flow ($v_{EX-P} = 0.85$ Mach) ignition occurred in the beginning of the mixing region, and the combustion temperatures locally approached the boron ignition temperature of 2000 K.

Tests at varying air-to-fuel ratio ($18 < a/f < 52$) and subsonic primary exhaust showed that ignition of the gaseous component always occurred in the beginning of the mixing region, and the local combustion temperatures exceeded 2000 K independently of a/f. With a flameholding/mixing device the local secondary chamber combustion temperatures were generally lower than in the tests with subsonic exhaust.

For studying the influence of boron and inert aluminum oxide particles on the ignition process of the gaseous components, the primary chamber in Fig. 2 was used. It consisted of the previously described solid propellant motor, the mixing section with oxygen injection, the blast tube with the two-nozzle arrangement, and an additional mixing section in which the particles were injected at steadily increasing mass flow rate by a hydraulically driven piston. The tests were made under conditions where the gaseous components did not ignite in the air without particles. Ignition of the gaseous components (although erratic in the beginning) was accomplished when a specific boron particle loading (M_b) was introduced into the primary chamber. After M_b increased to a second specific value, steady combustion occurred. The minimum M_b to initiate erratic and steady combustion was determined

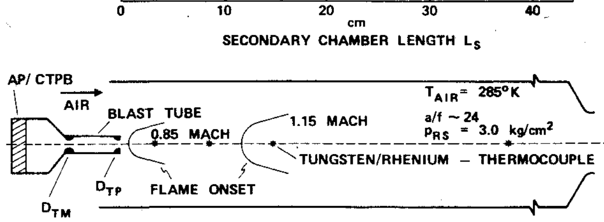

Fig. 1 Secondary chamber centerline temperatures and position of flame onset as a function of primary exhaust velocity.

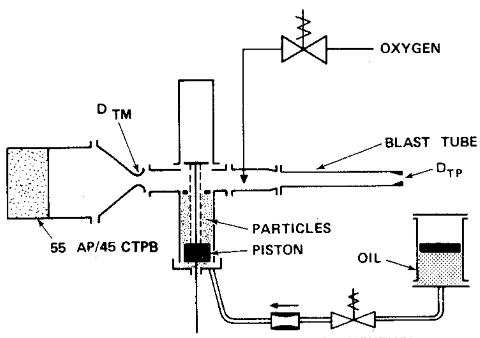

Fig. 2 Primary chamber for studying the influence of particulate fuels on the gaseous combustion in airstream.

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*General Engineer, Research Department, Aerothermochemistry Division.

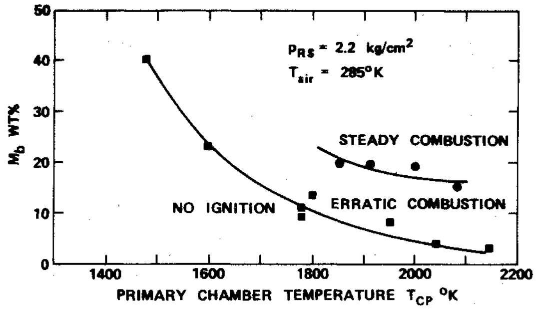

Fig. 3 Minimum boron loading needed to initiate erratic and steady combustion of the gaseous components as a function of primary chamber temperature for supersonic primary exhaust velocity.

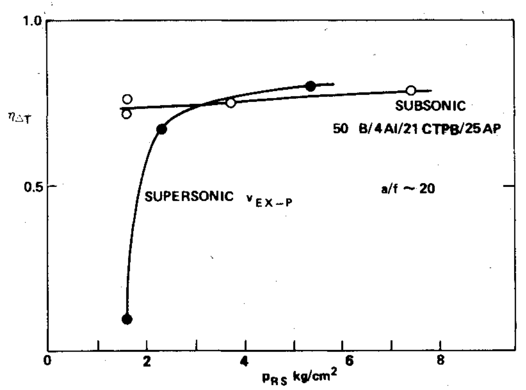

Fig. 4 Boron combustion efficiency as a function of secondary chamber pressure for supersonic and subsonic primary exhaust velocity.

as a function of T_{CP}, v_{EX-P}, and the solid propellant mass flow.

For supersonic v_{EX-P} the minimum M_b at which erratic combustion started increased from 3% at $T_{CP}=2050$ K to 40% at $T_{CP}=1500$ K (Fig. 3). For steady combustion, the minimum M_b needed was about 10% higher than for erratic combustion. At subsonic $v_{EX-P}$the minimum M_b for combustion was considerably lower than at supersonic v_{EX-P}. The results indicate that a boron-loaded solid propellant with $T_{CP}=1500$ K, and $M_b=30\%$ will burn under steady conditions at subsonic v_{EX-P} and $p_{RS}=2.2$ kg/cm^2; however, it will not ignite in the secondary chamber at supersonic v_{EX-P}.

With increasing propellant mass flow, the minimum M_b necessary to initiate ignition of the gaseous components decreased. The results indicate that a boron-loaded solid propellant with $M_b=20\%$ and $T_{CP}=1700$ K will not ignite in the secondary chamber at low propellant mass flow (0.04 kg/sec) and $p_{RS}=3.1$ kg/cm^2; however, it will ignite at higher mass flow (0.12 kg/sec).

Inert aluminum oxide particles did not initiate ignition of the gaseous components in the air under the same temperature and loading conditions as described for the tests with boron in Fig. 2. It is, therefore, believed that in the tests with boron, reactive boron species such as B_2O_2 and BOH produced atomic oxygen upon reaction with molecular oxygen in the mixing region with the air and caused ignition with the gaseous components.

For a boron-loaded solid boron propellant with 50%-B/4-Al/25-AP/21-CTPB the temperature rise combustion efficiency ($\eta_{\Delta T}$) was determined as a function of p_{RS} for decreased with decreasing p_{RS} with supersonic V_{EX-P}, however, $\eta_{\Delta T}$ was nearly independent of p_{RS} at subsonic v_{EX-P}.

The improvement of the boron combustion efficiency was achieved by optimizing the ignition process of the gaseous components. This result supports previous conclusions[1,2] that the low boron combustion efficiency at low secondary chamber pressure was caused by difficulties of igniting the gaseous components and not due to difficulties of igniting and burning boron particles at low pressure. The efficiency improvement can be explained considering the local *theoretical* combustion temperatures from the reaction of the gaseous components with the air. The theoretical temperatures of this reaction are *only* above the boron ignition temperature at the fore-end of the coaxial mixing region, and drop below the boron ignition temperature due to excess air mixing as the gases move downstream.[3] Therefore, high boron combustion efficiency can only be achieved when the gaseous components ignite in the beginning of the mixing region.

References

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[2]Schadow, K., "Study of Gas-Phase Reactions in Particle-Laden, Ducted Flows," *AIAA Journal*, Vol. 11, June 1973, p. 1042.

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