Appendix—Common Data for the Figures

The following data are common for all figures, except when the parameter is considered as a variable or explicitly expressed otherwise. The symbols b, c, ch, d, E, P, PR, and T_0 refer to burner (combustor), compressor, rocket chamber, diffuser (inlet), efficiency, pressure, pressure ratio, and stagnation temperature, respectively.

$\Delta P_b = 0$ (except in scramjet)	$T_{0,b} = 1800°R$
$E_b = 0.96$	$T_{ch} = 3600°R$
$E_d = E_n = 0.9$	$P_{ch} = 50$ atm
$T_b = 3600°R$	$PR_c = 20$

Acknowledgments

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Effects of Bypass Air on Boron Combustion in Solid Fuel Ramjets

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Introduction

THE use of boron as an additive in the polymeric fuel of a solid fuel ramjet (SFRJ) motor seems to be very promising because of its remarkably high theoretical heat of combustion.[1] However, extracting this energetic potential is a difficult task mainly due to the very complicated ignition and combustion processes of the boron particles.

Though the ignition and combustion of boron particles in oxidizing, temperature controlled atmospheres have been the subject of numerous studies,[2–5] there have been only few open literature publications[6–9] that provide information on the boron particles behavior inside a solid fuel ramjet motor.

The boron particles tend to accumulate and form large agglomerates on the fuel surface. As a result, the particles that enter the SFRJ flowfield are considerably larger[6–8] (up to 100 μ) than the original boron particles (typically below 10 μ).

Under regular conditions, the particles that are ejected from the fuel surface to the gas flowfield in the combustion chamber are covered by a thin boron oxide layer, serving as a barrier for further oxidation. The removal of this layer, mainly by evaporation of the oxide due to the particle heat up, sets the conditions for ignition.[2] Previous research by Natan and Gany[9] showed that for the conditions that exist in a solid fuel ramjet flowfield, the requirements for ignition of individual boron particles can barely coexist with the requirements for complete combustion of these particles. Natan and Gany[9] provided the following explanation to this phenomenon: Particles whose trajectories allow them sufficient residence time in the hot gas phase diffusion flame zone within the boundary layer, ignite fairly readily. However, even long residence times in this area do not permit high particle burning rates due to the low oxygen content in this zone. On the other hand, particles whose high ejection velocities bring them to the oxygen rich region, above the flame zone, may not ignite at all due to their short residence time in the hot environment. These peculiar constraints enable complete burning of relatively small particles (less than 30 μ) only, and only when they are ejected from the fuel surface at a very limited velocity range. The result is that the total fraction of boron that can burn within the combustion chamber is very little.

One method for improving the ignition process is by introducing in the fuel certain additives (such as Teflon® or titanium) that react with boron exothermically, thus producing the heat necessary for the ignition of the particles. Yet, the likely result of fast ignition does not promise that the particles can reach the oxygen rich zone and burn at high burning rates. Moreover, these additives may reduce the specific impulse of the motor. In general, most of the particles are able to ignite inside the grain port, but cannot burn completely.

Logically, if already ignited boron particles reach an oxygen rich environment, they can burn at relatively high burning rates. This can be achieved by separating the airflow that enters the SFRJ motor into two parts: 1) main flow that passes through the solid fuel port (main combustor), and 2) bypass flow which mixes with the main flow in a mixing chamber (afterburner), downstream of the main combustor.

Presumably, the use of bypass air may have a number of beneficial effects: 1) it promotes the ignition of boron particles because of the lower air mass flux through the main combustor resulting in a thicker and hotter flame zone[10] and increased residence times of the particles; 2) it enhances the combustion of the already ignited particles due to the better mixing of the particles with the air in the afterburner; and 3) it permits control of the solid fuel regression rate and the overall fuel-to-air ratio as a result of the effect of the main combustor mass flux on the fuel regression rate.

The main idea is to divide the motor into two sections, each performing different functions regarding the interactions of the boron particles with their surroundings. The first section is the main combustion chamber, where the solid fuel is placed. This section supplies the boron particles and provides the conditions necessary for their ignition (i.e., zones of high local temperatures). The second section, the afterburner, provides conditions where combustion of already ignited particles

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(coming from the first section) can be sustained. These conditions result from the mixing and close contact of the particles with high concentrations of fresh air.

The objective of the present work was to examine this idea and to investigate the effect of bypass air on the combustion behavior of boron particles moving in the flowfield of the SFRJ motor.

Physical Model

The physical model of the present study proposes different treatments for each of the two main sections. The model describing the flowfield and the combustion phenomena in the main combustor section is presented in detail in Ref. 9. According to the model, the flow in the main combustor was assumed to be steady, turbulent, reactive, axisymmetric, and of a boundary-layer type. The gas composition was described by the concentrations of O_2, N_2, gaseous fuel, H_2O vapor, and other combustion products. The governing conservation equations considered were: continuity, axial momentum, energy, and chemical species. The effective viscosity was taken as the sum of the laminar and turbulent contributions, and the turbulent viscosity was characterized by the Prandtl mixing length hypothesis. For the oxidation of the gaseous fuel a global, single step, reversible chemical reaction was used (O_2 + fuel $\rightleftharpoons$ products). The regression rate of the hydrocarbon solid fuel (HTPB) was calculated from the heat flux to the wall and the effective heat of gasification of the solid fuel, which included its sensible heat. The decomposition and vaporization of the solid fuel was assumed to occur at 800 K. On the axis of symmetry the derivatives of all dependent variables were taken as zero. At the intial cross section of the developing boundary-layer region, profiles of the dependent variables were specified, based on evaluation of the global amount of fuel burned in the recirculation zone. The numerical solution procedure of the gas flow was based on the GENMIX code by Patankar and Spalding.[11]

At the entrance to the afterburner, complete, adiabatic, constant pressure mixing between the main flow and the bypass air was assumed. The gaseous species were assumed to be unchanged during the mixing process. In reality, this process is rather complex and involves three-dimensional phenomena. Yet, since the main objective was to provide a more qualitative rather than a quantitative analysis, a simplified process was chosen for this purpose.

In the afterburner, a steady, one-dimensional reactive flow was considered. The equations considered were continuity, axial momentum, energy, and chemical species. The diffusion terms in the momentum and energy equations were neglected since the turbulent (eddy) transfer coefficients are relatively low in the flow direction.[12,13] The conditions at the end of the main combustor, along with the bypass air characteristics, were used as input for determining the initial conditions at the aft-mixing chamber.

The gas flow in both sections was considered to be decoupled from the particle influence. For the main combustion chamber this assumption is justified by the fact that most of the ignited particles burn at very low burning rates, thus they almost do not affect the gaseous flow. The flow in the afterburner may be affected by the burning particles mainly due to heat release. However, the objective of the present research was to characterize the combustion phenomena of the individual boron particles; therefore, as a first approximation, the influence of the particles on the flowfield could be neglected.

The equations describing the motion of the particles and their thermal behavior are presented in detail in Ref. 9. The boron particle motion was assumed to be dominated by the drag force resulting from the velocity difference between the gas and the particle. The thermal model considered for the ignition and combustion of the particles was based on King's theoretical model.[2,3] The local gas flow properties were used as the ambient conditions of the particles. Ignition of the particle was characterized by a complete removal of the boron oxide layer.

Results and Discussion

The investigation deals with the behavior of relatively large particles (30–50 μ). The ejection velocity and angle of a particle of a certain size determines its ignition location. The geometric locus of all ignition locations of particles of the same size, ejected at various velocities and angles within the main combustor, can be defined as the ignition zone,[10] and it is presented in Fig. 1. The zero point in the x-y axes interception represents the ejection point. The physical meaning of the ignition zone is that every particle (of a certain size) that intercepts the boundaries of this zone ignites. It seems that most particles are likely to ignite within the main combustor, except those ejected at very high ejection velocities. Most particles are ejected at low ejection velocities,[6] and sooner or later they enter the ignition zone and ignite. However, usually they do not completely burn inside the main combustor. The fraction of burned boron at the end of a 1-m-long, 20-cm-diam main combustor as a function of the ejection velocity is presented in Fig. 2 for 30-, 40-, and 50-μ particles. It can be seen that even at optimal conditions, large particles can hardly reach a 50% combustion efficiency, which is certainly not enough. The burning conditions of the boron particles in an SFRJ motor of a smaller diameter become even more difficult. In this case only 30% of the large size particles burn inside the main combustor at optimal conditions. The reason for this behavior is that for the same air mass flux through the motor, a similar solid fuel regression rate is obtained.[14] This increases the fuel-to-air ratio in the narrower motor, which means that less oxygen is available for the combustion of the boron, and as a result the particles burn at lower rates.

The axial location of the particle ejection from the fuel surface also affects the combustion behavior of the boron

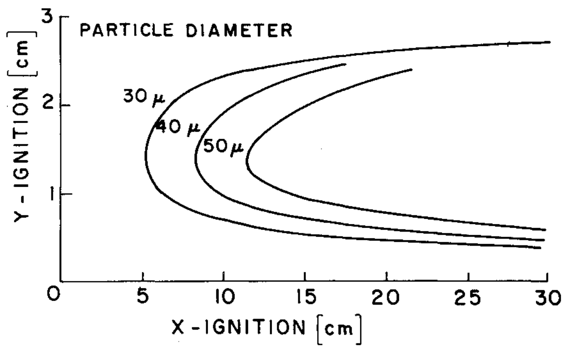

Fig. 1 Ignition zone of relatively large size particles.

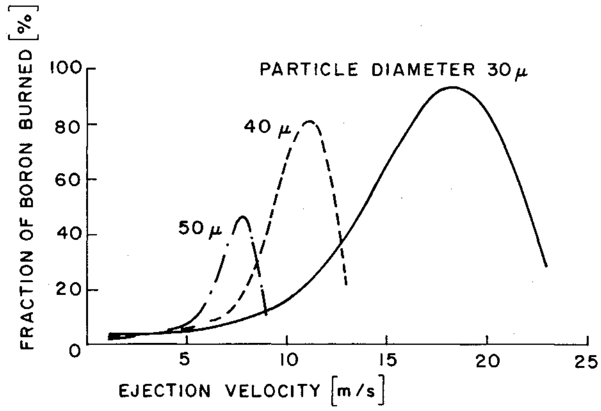

Fig. 2 Cumulative burned boron fraction at the downstream end of a 1-m-long main combustion chamber.

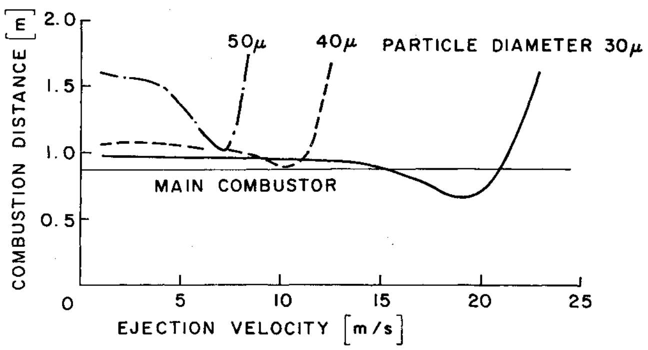

Fig. 3 Distance required for complete combustion of a boron particle when bypass air is added.

particles. For downstream locations, the smaller amounts of oxygen available and the shorter residence times result in lower combustion efficiencies of the boron. In these cases even the 30-μ particles cannot burn completely inside the main combustor.

The addition of fresh bypass air provides the necessary oxygen for the boron particles to complete their burning. The cooler gas flow resulting from the mixing process slows down the homogeneous reaction rates, but permits the boron to react with the available oxygen. The results are shown in Fig. 3. It is rather clear that most particles can burn within a 50-cm-long afterburner.

Conclusions

The combustion behavior of individual boron particles in the flowfield of an HTPB/Boron solid fuel ramjet motor with and without bypass air addition was investigated. The present work demonstrates that most boron particles cannot complete their burning within the main combustor of the motor. Therefore, in general, poor combustion efficiencies are expected for SFRJ motors employing boron (without ignition promoting additives) as a fuel ingredient. The use of an afterburner, where bypass air is added, was shown to permit complete combustion of the particles within a reasonable afterburner length, thus improving the combustion efficiency of the motor. It is believed that such an arrangement may be a significant step forward in utilizing the energetic potential of boron in SFRJ combustors.

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Approach to the Measurement of Burning-Surface Temperature of Boron

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Introduction

THE ignition and combustion processes of boron have been of great interest to many researchers in the field of combustion. This is due to the high volumetric and gravimetric heating values of boron, which provide more than twice the volumetric heating values of conventional hydrocarbon fuels for air breathing propulsion systems and substantially improve the performance of volume-limited vehicles.[1]

Based on the experimental studies of Macek and Semple,[2] a prominent and distinctive characteristic of the combustion of boron particles is that it almost invariably takes place in two successive stages. The first-stage ignition is a self-heating stage during which the boron particle is coated by a molten boric oxide layer through which oxygen and boron must diffuse to react with each other in order to provide reaction heat for vaporization of the oxide layer. As long as the sum of the reaction heat and convective and radiative heat-transfer from the hotter surroundings remains greater than the product of the oxide vaporization rate and heat of vaporization, the boron temperature will continue to rise. If this situation persists to the point at which the remaining oxide layer is sufficiently thin, a temperature runaway will occur, the oxide layer will be completely removed from the boron particle, and second-stage ignition, i.e., full-fledged combustion, will occur. If, on the other hand, the sum of reaction, convective, and radiative heat drops below the vaporization heat demand before the oxide layer is removed from the surface, the boron will not ignite.

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