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Combustion Characteristics of a Boron-Fueled Solid Fuel Ramjet with Aft-Burner

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The research deals with a theoretical evaluation of the concept of using an afterburner in a solid fuel ramjet motor, where bypass air is added, as a means of enhancing combustion efficiencies of boron containing fuels. A theoretical model is developed and solved numerically. A parametric investigation examines the effect of pressure, air mass flux, equivalence ratio, inlet air temperature, and the aft-burner length. The results reveal that good boron combustion efficiencies and high temperatures can be obtained at optimal conditions.

Nomenclature

A_f, A_b = forward and backward reaction kinetics coefficients
C_i = molar concentration of the i species
$\dot{C}_i$ = reaction rate of the i species
c_p = specific heat at constant pressure
D = diffusivity
D_{32} = Sauter mean diameter
d_B = boron particle diameter
E_f, E_b = activation energy of forward and backward reactions
Fu = hydrocarbon fuel
f = fuel to air ratio
f_M = fraction of molten phase of boron in the particle
h_p = enthalpy of the particles
h = gas-particle heat transfer coefficient
k = number of particle groups
M = molecular weight
m = mass
$\dot{m}$ = mass flow rate
n_j = number of particles per unit volume of the j group
Pm = heterogeneous reaction products
Pr = homogeneous (gas-phase) reaction products
Pr_{eff} = effective Prandtl number
p = pressure
q_R = heat of Fu-O_2 reaction per unit mass of Fu
q_{RB} = heat of B-O_2 reaction per unit mass of B
R = universal gas constant
R_B = molar burning rate of boron particle
T = temperature
u = axial velocity
w = bypass to main mass flow rate ratio
x = axial coordinate
y_i = mass fraction of the i species
β = stoichiometric coefficient defined in Eq. (6)
ΔH_M = heat of fusion of boron
ε = emissivity
η_B = boron combustion efficiency
θ = parameter defined in Eq. (8)
λ = boron mass fraction in solid fuel
ν = hydrocarbon fuel to oxygen stoichiometric mass ratio
ν' = hydrocarbon fuel to air stoichiometric molar ratio
ξ = boron to oxygen stoichiometric mass ratio
ρ = total density
ρ_B = boron density
ρ_f = fluid density
ρ_g = gas density
ρ_p = solid (or liquid) phase density
σ = Stephan-Boltzman constant
φ = equivalence ratio

Subscripts
a = air
B = boron
b = bypass
c = main combustor region
Fu = hydrocarbon fuel
g = gas
i = main combustor inlet
j = particle group
p = particle
RAD = radiation
st = stoichiometric
t = total

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Introduction

THE remarkably high theoretical heat of combustion of boron with air[1] makes it an attractive fuel ingredient for air breathing propulsion systems. Thus, extensive fundamental studies on boron particles in controlled oxidizing atmospheres[2-5] have been performed. These investigations revealed peculiar ignition and combustion behavior resulting from the formation of a molten boron oxide layer on the particle, which serves as a barrier for fast oxidation. Since the conditions for ignition imply the removal of this oxide layer that can take place mainly by means of evaporation requiring temperatures which exceed 1900 K, it has generally been accepted that extraction of the energy potential of the boron should be a difficult task.[6]

The recent interest in high energy solid fuel ramjet (SFRJ) engines has brought up the possibility of adding boron to the polymeric matrix of the commonly used hydrocarbon fuel. A number of experimental studies[7-9] have provided some information on the combustion phenomena of boron-containing fuels. For instance, it has been shown that as a result of agglomeration or fuel surface flaking, the particles ejected to the flowfield may be much larger than the original boron particles. A detailed theoretical study by Natan and Gany[10] indicated that the SFRJ combustor flowfield is inherently un-

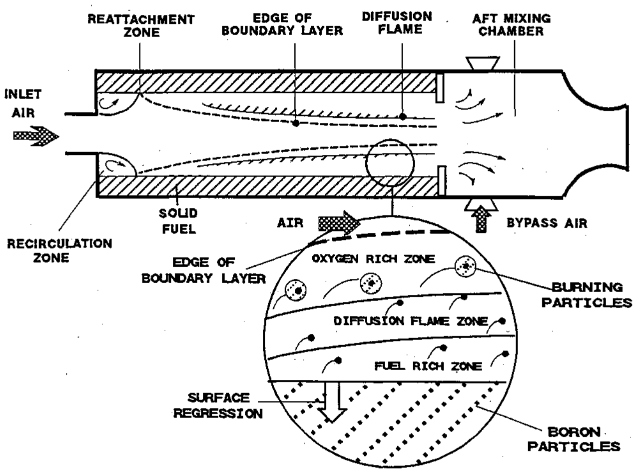

Fig. 1 Flowfield in the main combustion chamber of a boron-containing metalized solid fuel ramjet.[20]

favorable for efficient boron combustion. The requirements for the boron particle ignition may generally contradict the conditions necessary for sustained combustion. Optimal ignition conditions are obtained for particles whose trajectories coincide with the gas phase diffusion flame zone, where the gas temperature and the water vapor fraction are relatively high, promoting the removal of the oxide layer. On the contrary, the oxygen mass fraction in this zone is rather limited due to the homogeneous reaction with the gaseous hydrocarbon fuel. This results in low burning rates of the boron particles. Best combustion conditions are obtained for particles whose trajectories lead them to the oxygen-rich zone above the flame zone (Fig. 1).[11] Natan and Gany[10] further indicated that, even though the interactions of the boron particles with the surrounding gas are much affected by the particle properties upon ejection from the surface (e.g., size, temperature, velocity, and direction), most of the particles (up to 50-μ diameter) can ignite inside the combustion chamber. However, only few can sustain combustion, and a rather limited portion of boron is expected to burn completely before leaving the motor. Consequently, poor combustion efficiencies are expected for SFRJs employing boron containing fuels.

Presuming that already ignited boron particles can burn at relatively high burning rates, once they encounter an oxygen-rich environment, Natan and Gany[12] proposed the idea of an afterburner, where bypass air is added, as a means to establish the necessary situation for efficient boron combustion. The general concept was to divide the SFRJ combustor into two major sections, each performing a different function regarding the boron: 1) the main combustor section, where the solid fuel is placed, whose function is to provide the fuel ingredients, including the boron, and to enable the ignition of the boron particles; and 2) the aft-burner section, where bypass air is added, whose function is to enable good combustion of the boron by exposing the already ignited boron particles to high concentrations of fresh air. Other advantages of such arrangement, e.g., control of the fuel regression rate, were also mentioned. Reference 12 examined the general idea in a preliminary manner by studying the behavior of individual boron particles which are ejected into a typical SFRJ combustor environment and continue in the aft-burner, without accounting for the contribution of the boron to the overall combustion process. That study indicated that even large (50 μ) boron particles can burn within a 50-cm-long afterburner.

The objective of the present work was a theoretical study of the combustion phenomena in a boron-containing solid fuel ramjet with an air augmented afterburner. Detailed modeling of the two-phase reacting flowfield of the two major combustor sections, 1) the main combustor and 2) the afterburner, was developed and solved numerically. A parametric investigation of the factors that affect the combustion of the particles was conducted to obtain optimal operating conditions.

Physical Model

Basic Assumptions

The SFRJ combustor is divided into two major sections: 1) main combustor and 2) afterburner, connected by a mixing zone (Fig. 2),[11] which contains the bypass air inlet ports. Each of these sections performs different functions regarding the interactions of the boron particles with their surroundings and has different flow and combustion characteristics. The present research is focused in particular on the combustion phenomena in the aft-burner, since the most significant part of the boron combustion occurs in that section.

According to the conclusions of Refs. 10 and 12, most of the boron particles are ignited prior to their entrance to the aft-burner as a result of their interactions with the combusting gas in the main combustor section. It is also indicated that, in practice, the amount of boron burned in the main combustor is negligible. Hence, it is obvious that most of the boron combustion process takes place in the afterburner, where a sufficient amount of oxygen is available.

The complete model describing the flowfield and the combustion phenomena in the main combustion chamber is presented in detail in Ref. 10. This region is characterized by a turbulent, axisymmetric, boundary-layer type, reacting gas flowfield, which is practically decoupled from the particles influence. The two-phase flow properties at the downstream end of the main combustor, along with the air added at the mixing zone, set the initial flow conditions of the aft-burner.

With the focus on the afterburner combustion phenomena, the mixing process itself has not been investigated in detail. Presuming that good mixing between the flow coming from the main combustor and the bypass air can be achieved, one may avoid the efforts involved in the detailed solution of a three-dimensional mixing process, using a simplified approximation of an instantaneous, adiabatic, constant pressure, complete mixing. The chemical species are assumed unchanged during the mixing process.

In the aft-burner, a steady, two-phase, one-dimensional reactive flow is considered. The approximation of a simplified mixing process and the one-dimensional flow analysis which takes into account the complex phenomena involved in the combustion of boron particles, can provide fundamental information and physical insight to the problem.

The model uses gas-phase flow which contains oxygen, nitrogen, gaseous fuel, and both homogeneous (e.g., H_2O, CO_2) and heterogeneous (B_2O_3) reaction products. Global reversible reaction kinetics are assumed for the homogeneous reaction. All gases are assumed to be perfect. The velocity of the boron particles is practically equal to that of the gas stream, as indicated by the calculations presented in Ref. 10. Since the volume fraction of the solid (or liquid) phase is small relative to that of the gas, the fluid density is practically the same as the gas density.

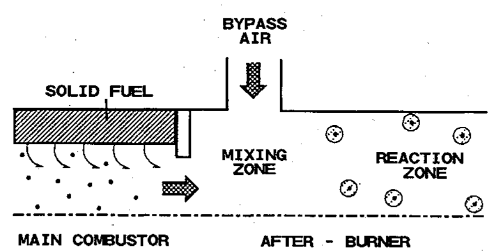

Fig. 2 Schematic of the main combustor and afterburner.[20]

Basic Definitions

The fuel to air ratio f_c at the downstream end of the main combustor is defined by

$$f_c = (\dot{m}_{\mathrm{Fu}}/\dot{m}_{a,i}) \tag{1}$$

while the total fuel to air ratio, which includes the boron mass and the bypass air, is defined by

$$f_t = [(\dot{m}_{\mathrm{Fu}} + \dot{m}_{\mathrm{B}})/(\dot{m}_{a,i} + \dot{m}_{a,b})] \tag{2}$$

The ratio between the mass of boron and the total fuel mass (boron and hydrocarbon fuel) λ, is given by

$$\lambda = [m_{\mathrm{B}}/(m_{\mathrm{B}} + m_{\mathrm{Fu}})] = [\dot{m}_{\mathrm{B}}/(\dot{m}_{\mathrm{B}} + \dot{m}_{\mathrm{Fu}})] \tag{3}$$

The global reversible homogeneous chemical reaction between the hydrocarbon fuel and the air is described by

$$Fu + \nu'(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightleftharpoons Pr + 3.76\nu'\mathrm{N_2} \tag{4}$$

The total chemical reaction between fuel (including boron) and air is

$$Fu + 2\beta\mathrm{B} + (\nu' + 1.5\beta)(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightleftharpoons Pr + \beta Pm + 3.76(\nu' + 1.5\beta)\mathrm{N_2} \tag{5}$$

where for the boron/oxygen reaction unidirectional kinetics are assumed. β is defined as

$$\beta = (M_{\mathrm{Fu}}/2M_{\mathrm{B}})[\lambda/(1 - \lambda)] \tag{6}$$

The relation between the stoichiometric fuel to air ratios of these two reactions (homogeneous and total) is given by

$$f_{\mathrm{st},t} = f_{\mathrm{st,Fu}}/(1 - \theta\lambda) \tag{7}$$

where

$$\theta = 1 - (3/2\nu')(M_{\mathrm{Fu}}/2M_{\mathrm{B}}) \tag{8}$$

Combining Eqs. (1–3), (7), and (8), the ratio between bypass and main mass flow rates (bypass ratio) w, is found to be

$$w = (\varphi_c/\varphi_t)[(1 - \theta\lambda)/(1 - \lambda)] - 1 \tag{9}$$

This formulation permits computation of the bypass ratio w required for a desired total equivalence ratio (φ_t) and a certain boron mass fraction in the solid fuel λ.

Governing Equations

For the two-phase flow, the model chosen is based on the spray combustion model of Williams.[13] The boron particle size distribution is represented by k diameter groups, while n_j is the number of particles per unit volume of the j group. The density of the solid or liquid phase (ρ_p) is defined by

$$\rho_p = \sum_{j=1}^{k} \rho_{\mathrm{B}} n_j \frac{\pi}{6} d_{\mathrm{B}j}^3 \tag{10}$$

Assuming that the fluid density is equal to the gas density, the total density is defined by

$$\rho = \rho_f + \rho_p = \rho_g + \sum_{j=1}^{k} \rho_{\mathrm{B}} n_j \frac{\pi}{6} d_{\mathrm{B}j}^3 \tag{11}$$

The one-dimensional continuity equation in the afterburner is expressed by

$$\frac{\mathrm{d}}{\mathrm{d}x}(\rho_g u_g + \rho_p u_p) = 0 \tag{12}$$

Assuming equal gas and particles velocities ($u = u_g = u_p$), Eq. (12) can be written

$$\frac{\mathrm{d}}{\mathrm{d}x}(\rho u) = 0 \tag{13}$$

Momentum equation

$$\frac{\mathrm{d}}{\mathrm{d}x}(\rho_g u^2 + \rho_p u^2) = -\frac{\mathrm{d}p}{\mathrm{d}x} + \frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{4}{3}\mu_{\mathrm{eff}}\frac{\mathrm{d}u}{\mathrm{d}x}\right) \tag{14}$$

Energy equation

$$\frac{\mathrm{d}}{\mathrm{d}x}\left[\rho_g u(c_p T_g + y_{\mathrm{Fu}} q_R) + \rho_p u h_p + \rho u \frac{1}{2} u^2\right] = \frac{c_p \mu_{\mathrm{eff}}}{Pr_{\mathrm{eff}}}\frac{\mathrm{d}^2 T_g}{\mathrm{d}x^2} + \frac{4}{3}\mu_{\mathrm{eff}}\left[\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)^2 + u\frac{\mathrm{d}^2 u}{\mathrm{d}x^2}\right] \tag{15}$$

where h_p is the specific enthalpy of the particles, which includes the chemical energy and is given by

$$h_p = \frac{\sum_{j=1}^{k} \rho_{\mathrm{B}} n_j \frac{\pi}{6} d_{\mathrm{B}j}^3 (c_{p\mathrm{B}} T_{pj} + \Delta H_M f_{Mj} + q_{R\mathrm{B}})}{\sum_{j=1}^{k} \rho_{\mathrm{B}} n_j \frac{\pi}{6} d_{\mathrm{B}j}^3} \tag{16}$$

where, $q_{R\mathrm{B}}$ is the heat of combustion of boron per unit mass, and f_{Mj} is the ratio between the molten and total mass of boron particles that belong to the j group. This expression of the particles enthalpy [Eq. (16)] is rather convenient. The molten fraction (f_{Mj}) is equal to zero for particle temperature below 2540 K, it rises during the constant temperature (2450 K) melting process to reach the value of 1 for completely molten particles, and only then can the temperature increase further. By including q_{RB} in h_p there is no need for a source term. A decrease of the diameter of the particles causes decrease of the $d_{\mathrm{B}j}^3 q_{R\mathrm{B}}$ term and increases the other terms.

The axial diffusion terms in the momentum and energy Eqs. (14) and (15), can be neglected, since the turbulent (eddy) transfer coefficients are relatively low in the axial direction. This assumption is rather common in the literature (e.g., the well-stirred reactor of Longwell and Weiss, described by Glassman,[14] as well as the plug flow reactor used by Hautman et al.[15]). The dominant contribution is due to the convection and source terms. Neglecting also the dissipation term in the energy equation, Eqs. (14) and (15) yield

$$\rho u \frac{\mathrm{d}u}{\mathrm{d}x} = -\frac{\mathrm{d}p}{\mathrm{d}x} \tag{17}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\left[\rho_g u(c_p T_g + y_{\mathrm{Fu}} q_R) + \rho_p u h_p + \rho u \frac{1}{2} u^2\right] = 0 \tag{18}$$

The rate of change of the particles diameter is described by

$$u\frac{\mathrm{d}d_{\mathrm{B}j}}{\mathrm{d}x} = -\frac{2R_{\mathrm{B}j} M_{\mathrm{B}}}{\pi d_{\mathrm{B}j}^2 \rho_{\mathrm{B}}} \tag{19}$$

The temperature (T_{pj}) or the molten fraction (f_{Mj}) of the particles change at a rate which is dictated by the heat gain from the B-O_2 reaction and the heat losses to the surroundings. This particle energy balance is given by

$$u\left[c_{pB}\frac{dT_{pj}}{dx}+\Delta H_M\frac{df_{Mj}}{dx}\right]=\frac{R_{Bj}M_Bq_{RB}+\pi d_{Bj}^2[\bar h(T_g-T_{pj})+\sigma\varepsilon(T_{RAD}^4-T_{pj}^4)]}{\frac{\pi}{6}d_{Bj}^3\rho_B} \tag{20}$$

The chemical reactions considered are

$$Fu+\nu O_2\rightleftharpoons(1+\nu)Pr \tag{21}$$

$$B+\xi O_2\rightarrow(1+\xi)Pm \tag{22}$$

The species reaction rates can be written

$$\dot C_{Pr}=-(1+\nu)\frac{M_{Fu}}{M_{Pr}}\dot C_{Fu} \tag{23}$$

$$\dot C_{Pm}=(1+\xi)\frac{M_B}{M_{Pm}}\sum_{j=1}^{k}n_jR_{Bj} \tag{24}$$

$$\dot C_{O_2}=\nu\frac{M_{Fu}}{M_{O_2}}\dot C_{Fu}-\xi\frac{M_B}{M_{O_2}}\sum_{j=1}^{k}n_jR_{Bj} \tag{25}$$

$$\dot C_{N_2}=0 \tag{26}$$

The homogeneous reaction rate is given by[10]

$$\dot C_{Fu}=-A_fe^{-E_f/RT}C_{Fu}C_{O_2}+A_be^{-E_b/RT}C_{Pr} \tag{27}$$

The molar consumption rate (R_{Bj}) of boron particles burning in a diffusion controlled regime is described by

$$R_{Bj}=2\pi d_{Bj}(\rho_gD/M_B)\ell n[1+0.677(M_{O_2}/\rho_g)C_{O_2}] \tag{28}$$

However, when the particle diameter becomes small (below 10 μ), the burning process may be kinetically controlled. In this case the particle burning rate (R_{Bj}) is calculated from the following expression which is based on the experimental data by Macek and Semple[16] (written in SI units):

$$R_{Bj}=1.5\times10^{-3}\pi d_{Bj}^2\rho_g/M_B \tag{29}$$

The species conservation equation can be written

$$\frac{d}{dx}(\rho_guy_i)=D_{i,g}\frac{d^2(\rho_gy_i)}{dx^2}+M_i\dot C_i \tag{30}$$

By assuming that the diffusion term is negligible relative to the convection and source terms, Eq. (30) becomes

$$\frac{dC_i}{dx}=\frac{1}{u}\left(\dot C_i-C_i\frac{du}{dx}\right) \tag{31}$$

where the terms (dC_i/dt) are expressed in Eqs. (23–27). After some mathematical rearrangement, a system of $(8+3k)$ first-order differential equations is received: continuity (13), momentum (17), energy (18), five equations for the chemical species (31), k equations for d_{Bj} (19), k equations for T_{pj}, and k equations for f_{Mj} (20).

Numerical Solution

The whole system is numerically solved by a computer code. The numerical solution for the gas flow in the main combustor (first section) is based on GENMIX code by Patankar and Spalding,[17] which also calculates the fuel regression rate, providing the hydrocarbon and boron mass addition. The $(8+3k)$ governing equations of the flow in the aft-burner are solved by employing an IMSL routine for the solution of ordinary differential equations by the Gear's method.[18] At the end of the main section (1-m long) the flow properties are integrated and the local fuel to air ratio (f_c) as well as the amount of unburned boron are calculated. Accordingly, the bypass ratio w, and the mass flow rate of the bypass air $\dot m_{a,b}$, required for the desired theoretical total equivalence ratio, are computed. In the mixing chamber, the flow velocity, temperature, and composition are calculated based on the assumptions mentioned previously.

At the entrance to the aft-burner, an initial distribution of the boron particles is provided. The two-phase flow equations are solved at each step of the grid (1 mm), and the flow properties as well as the particles properties and distribution are computed.

Results and Discussion

One of the main goals of the present research was to investigate the effect of various parameters on boron combustion when bypass air is used. The progress in boron combustion was characterized by the portion of boron burned, termed as the boron combustion efficiency η_B. The influence of the following factors on η_B was studied: pressure, total equivalence ratio, air mass flux through the main combustion chamber, inlet air temperature, boron loading in the solid fuel, and aft-burner length.

The nominal (reference) conditions used in this investigation were—inlet gas temperature, 1000 K; pressure, 1 MPa; total equivalence ratio, 0.8; boron loading in the solid fuel, 50%; and air mass flux through the main combustor, 85 kg/m^2 s. In the cases studied, polydisperse initial distributions consisting of particles of diameters between 15–55 μ were used. The initial particle size distribution was chosen to fit particle sizes measured in experimental investigations with boron containing solid fuel ramjets.[7–9] The results exhibited slight variations for moderate variations in the initial particle size distributions in which D_{32} was kept constant. The initial temperatures of the particles in the afterburner were chosen between 2300 K (the large particles) and 2500 K (the small ones), with molten material fractions (f_{Mj}) between 0 and 1 depending on the particle size, in accordance with the calculations made in Ref. 10. The results showed that if the particles are assumed to be already ignited at the entrance to the aft-burner, the initial temperature of the particles has almost no effect on the overall performance. Since the oxygen mass fraction is high in the vicinity of the particles, equilibrium temperature is reached relatively fast and remains constant thereafter.

A characteristic composition of the species along the afterburner at the reference conditions is presented in Fig. 3. The oxygen mass fraction decreases rather fast as a result of

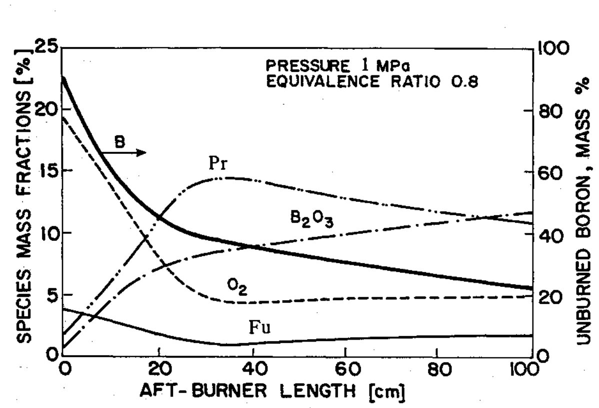

Fig. 3 Characteristic mass fractions of the species along the aft-burner.

both the homogeneous and heterogeneous reactions. In the upstream part of the aft-burner the mass fraction of B_2O_3 (Pm) as well as that of the homogeneous reaction products (Pr) increase. Downstream, where the gas temperature exceeds 2500 K (after 0.4 m, approximately), dissociation of the homogeneous reaction products begins, the fraction of Pr decreases, and the released oxygen is consumed by the boron. The consumption rate of the boron seems to be very fast at the beginning, but the heterogeneous reaction rate slows down after approximately 20 cm, when the oxygen mass fraction becomes low.

The oxygen mass fraction, the gas temperature, and η_B along the aft-burner are presented in Figs. 4, 5, and 6, respectively, for 10, 50, and 90% boron loadings in the solid fuel. The 10% boron composition closely represents the hydrocarbon fuel behavior, while the 90% boron (which is impractical) represents the behavior of boron. In Fig. 4 the shape of the 10% boron differs essentially from the 90% curve. This is due to the different character of the reaction involved. The cold bypass air mixes with the main stream coming from the main combustor, produces low gas temperatures, and this

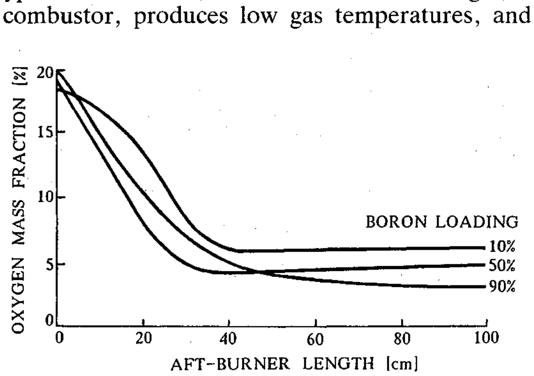

Fig. 4 Oxygen mass fraction along the aft-burner for various boron loadings.

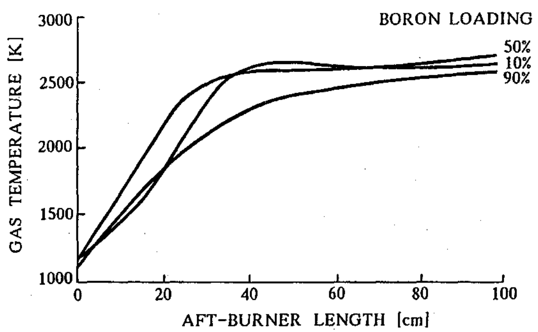

Fig. 5 Gas temperature along the aft-burner for various boron loadings.

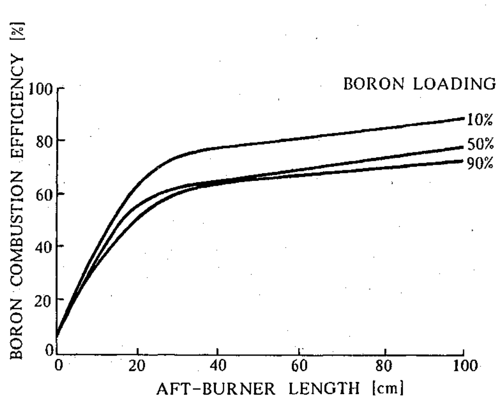

Fig. 6 Boron combustion efficiency (η_B) along the aft-burner for various boron loadings.

affects the homogeneous reaction in a different way than the heterogeneous reaction. For 10% boron loading [90% hydrocarbon (HC) fuel], the homogeneous reaction is dominant, and the low temperature immediately after the mixing zone slows down the reaction rate. On the contrary, for the 90% boron loading, the low initial temperature has only a little effect on the heterogeneous reaction rate, therefore, the consumption rate of oxygen is rather high. In the 50% boron case the heterogeneous exothermic reaction causes an increase in the gas temperature (Fig. 5), which accelerates the homogeneous reaction rate, hence, the oxygen consumption rate is higher compared to the other two cases. It has to be noted that, in general, the presence of already ignited hot boron particles in the mixture enhances the homogeneous reaction rate, and high temperatures may be obtained faster than in cases where the fuel is pure hydrocarbon and bypass air is used.

Figures 5 and 6 reveal that the gas temperature as well as the boron combustion efficiency for 50% boron are higher than for 90% boron loading. This seems rather peculiar since, for fixed total equivalence ratio, the oxygen mass fraction available in the 90% boron case is higher than in the 50% case. The reason for this lies in the fact that in order to obtain the same total equivalence ratio in both cases, the bypass air mass flow rate, required in the case of 90% boron loading, is much higher than in the case of 50% boron. This additional bypass air causes the flow to accelerate to higher velocities. The higher velocities imply shorter residence times, resulting in lower combustion efficiencies and gas temperatures.

Increasing the air mass flux in the main combustor results in increasing the fuel regression rate, yet decreasing the fuel to air ratio at the downstream end of the main combustor. Hence, the bypass ratio w required for a constant equivalence ratio is less for high main air mass fluxes than for low ones. Nevertheless, the increase in the main air mass flux results in an increase in the flow velocity in the aft-burner, which reduces the residence time of the particles. Consequently, lower gas temperature and boron combustion efficiency are to be expected (Figs. 7 and 8).

Essentially the burning rate of the boron particles is independent of pressure.[3] Macek[19] indicates a certain dependence on pressure for the low pressure range (under 1 atm), where the burning rate of the particles is kinetically controlled. For the typical SFRJ conditions, where the pressure is rather high, the combustion process is mainly diffusion controlled. The effect of pressure is expressed through the flow velocity. For the same conditions of main air mass flux and total equivalence ratio, high pressure results in low gas velocities. The low gas velocity increases the residence time of the particles, and higher gas temperatures together with

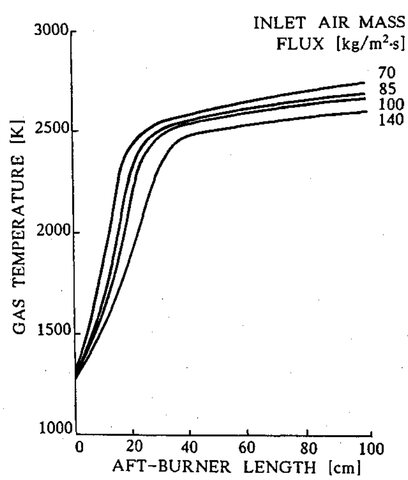

Fig. 7 Gas temperature along the aft-burner for various values of air mass flux through the main combustion chamber.

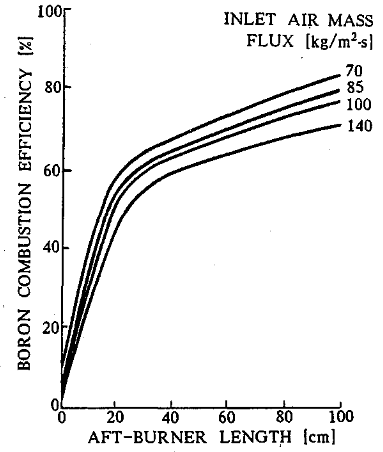

Fig. 8 Boron combustion efficiency (η_B) along the aft-burner for various values of air mass flux through the main combustion chamber.

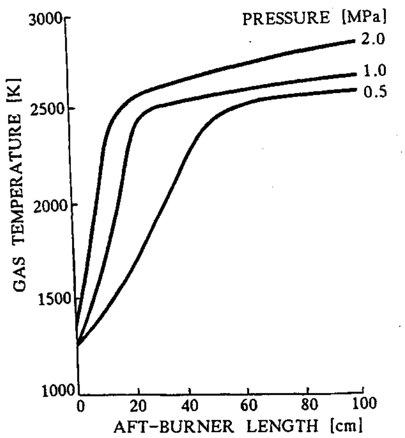

Fig. 9 Gas temperature along the aft-burner for various motor pressures.

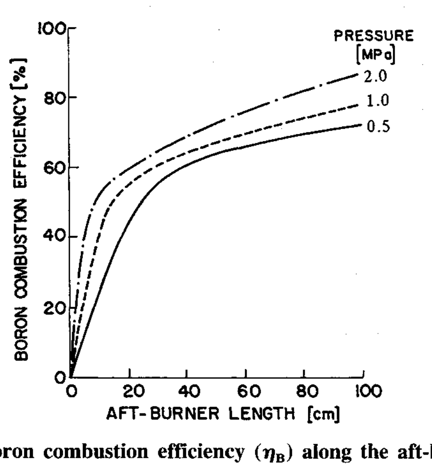

Fig. 10 Boron combustion efficiency (η_B) along the aft-burner for various motor pressures.

better combustion efficiencies are obtained (Figs. 9 and 10). However, it should be noted that the homogeneous reaction is pressure dependent, thereby affecting the overall performance, especially in cases of low boron loadings. In these cases, the boron particles encounter an oxygen rich environment, therefore, high boron burning rates can be obtained, however, at low motor pressures the gas temperatures may not be high.

The total equivalence ratio can be controlled by the bypass airflow rate. Introducing bypass air increases the oxygen mass fraction, thus enhancing the burning rate of the particles. On the other hand, it also increases the flow velocity, which results in a decrease in the residence time of the particles in the aft-burner.

The gas temperature and the boron combustion efficiency along the aft-burner, with the total equivalence ratio as the free parameter, are presented in Figs. 11 and 12, respectively, for a 50% boron loaded solid fuel. The boron combustion efficiency decreases with increasing the equivalence ratio as

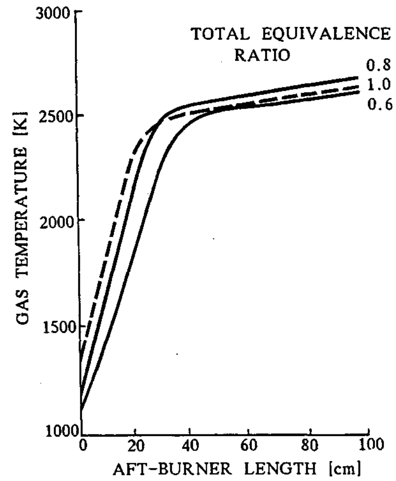

Fig. 11 Gas temperature along the aft-burner for various values of φ_t.

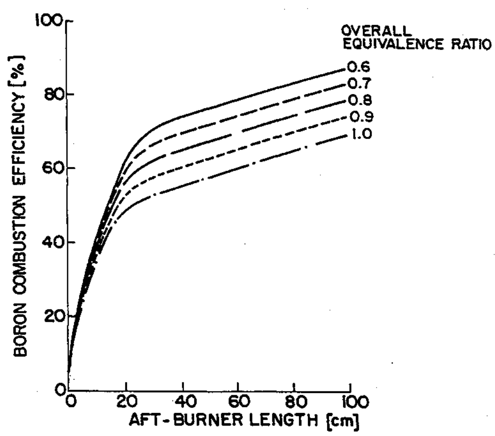

Fig. 12 Boron combustion efficiency (η_B) along the aft-burner for various values of φ_t.

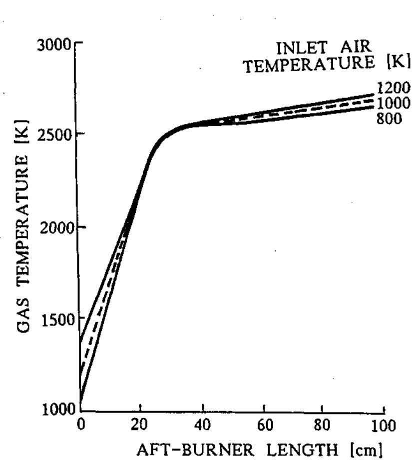

Fig. 13 Gas temperature along the aft-burner for various inlet air temperatures.

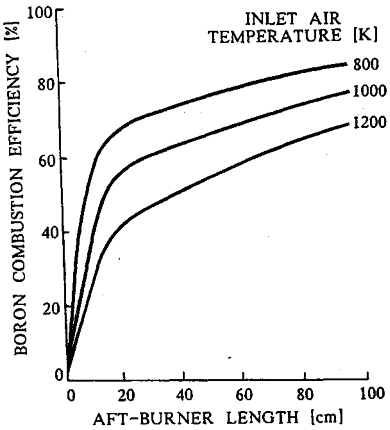

Fig. 14 Boron combustion efficiency (η_B) along the aft-burner for various inlet air temperatures.

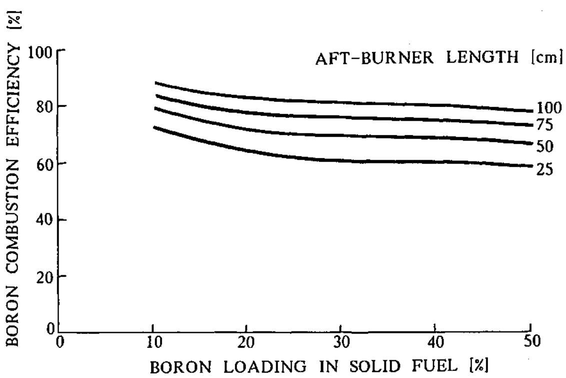

Fig. 15 Boron combustion efficiency (η_B) at the downstream end of aft-burners of various lengths as function of the boron loading in the solid fuel.

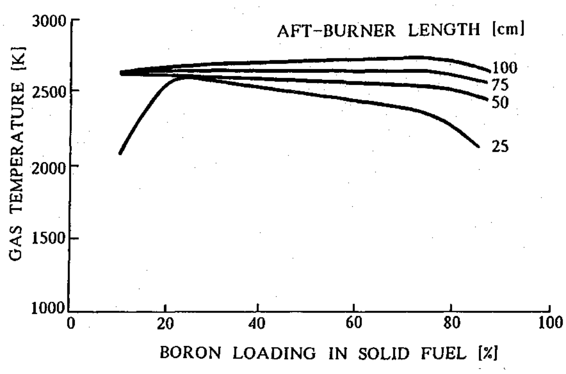

Fig. 16 Gas temperature at the downstream end of aft-burners of various lengths as function of the boron loading in the solid fuel.

a result of the decrease in the oxygen mass fraction (Fig. 12). In the upstream part of the aft-burner the gas temperature (Fig. 11) increases with increasing equivalence ratio due to the homogeneous reaction. At a distance of approximately 40 cm, a maximum gas temperature is obtained for equivalence ratio of $\varphi_t = 0.8$. This optimal value of φ_t results from equilibrium conditions between the various parameters that affect the whole process. Changes in φ_t affect both the heterogeneous and homogeneous reactions. The oxygen mass fraction decreases with increasing φ_t, causing lower heterogeneous reaction rates, and therefore, less heat release. On the other hand, a high φ_t tends to increase heat release from the homogeneous reaction. The gas temperature is determined from the combination of these two effects. The homogeneous reaction becomes dominant in low boron loading cases. In addition, high values of φ_t require less bypass air, hence, the flow velocity is low and the residence time of the particles in the aft-burner is longer.

The air inlet temperature results from the flight Mach number at a certain altitude and it is connected with the motor pressure. However, in order to isolate the effect of temperature on boron combustion, pressure was assumed constant. For the same inlet air mass flux and pressure, an increase in temperature results in a decrease in density and, hence, an increase in the flow velocity. On the other hand, high temperatures strongly enhance the homogeneous reaction and slightly enhance the heterogeneous reaction through its effect on the term $\rho_g D$ in a diffusion controlled regime. The gas temperature and the boron combustion efficiency for a 50% boron loading at various inlet air temperatures are presented in Figs. 13 and 14, respectively. It seems that the gas temperature is not affected much by the air temperature, however, the combustion efficiency of boron decreases with increasing air temperature. High inlet temperature accelerates the homogeneous reaction rate, which produces even higher flow velocities, and the residence time of the particles is decreased. The effect of the inlet air temperature becomes stronger at low boron loadings, where the homogeneous reaction is dominant.

It is easy to realize that a long aft-burner is needed in order to achieve complete combustion of the boron particles. In most practical cases the space required for the aft-burner can be utilized by filling it with solid propellant, which serves to boost the missile during the initial stage until it reaches the desirable takeover Mach number. Nevertheless, a long aft-burner adds undesirable weight to the missile, and the gain from the boron combustion might not justify the disadvantage of additional weight. There is no doubt that the combustion efficiency of boron increases with increasing the aft-burner length, and decreases with increasing the boron loading in the solid fuel while keeping the total equivalence ratio constant at $\varphi_t = 0.8$ (Fig. 15). However, for boron loadings between 25–40%, the rate of decrease of the combustion efficiency becomes moderate, even close to zero. Moreover, for aft-burners longer than 30 cm, the gas temperature, which characterizes the energetic performance of the motor, stays almost constant while the boron loading is increased (Fig. 16). This phenomenon is a result of the following reasons. When the boron loading is high, the oxygen mass fraction is insufficient to provide a fast burning rate; on the other hand, for low boron loadings, the HC fuel "steals" the oxygen from the boron particles. However, intermediate values of boron loadings, which imply high temperatures due to the contributions of both gas-phase and heterogeneous reactions, result in dissociation of the homogeneous reaction products, thus producing more oxygen for the boron particles. For equivalence ratios close to 1, the results presented in Figs. 15 and 16 lead to the conclusion that the specific impulse of the motor may decrease with increasing the boron loading. On the contrary, for low equivalence ratios (close to 0.6), the research results indicate that though the boron combustion efficiency decreases with increasing the boron loading, the gas temperature has a distinct maximum value at intermediate values of boron loadings (30–40%). This implies the existence of an optimal value of boron loading, in which the specific impulse or the motor thrust may be maximized, depending on the total equivalence ratio, the motor pressure, and the air mass flux.

The current theoretical results agree well with the tendency reflected by recent experimental data of Natan and Netzer[20] showing that the combustion efficiency of a boron fueled SFRJ motor increases almost linearly with increasing bypass ratio. In Ref. 20 the combustion efficiency was defined as the ratio between measured and theoretical temperature rise in the motor. The theoretical adiabatic flame temperature was calculated by assuming equilibrium conditions. This definition of the combustion efficiency makes the quantitative comparison between the theoretical results of the present work and the experimental results of Natan and Netzer difficult, although it proves qualitatively the validity of the present analysis.

Concluding Remarks

The concept of using an afterburner where bypass air is added in order to increase the combustion efficiencies of boron containing solid fuel ramjets has been examined. A theoretical model has been developed and numerically solved. The analysis indicates that a combination of various effects on the homogeneous and the heterogeneous reactions determines the nature of the combustion phenomena and the combustion efficiency of the boron particles. In general, high pressures as well as low equivalence ratios increase the combustion efficiency of boron particles. Experimental results from the literature verify qualitatively the theoretical model.

The results demonstrate that the use of bypass air is essential for achieving high boron combustion efficiencies and seems to be a practical solution.

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