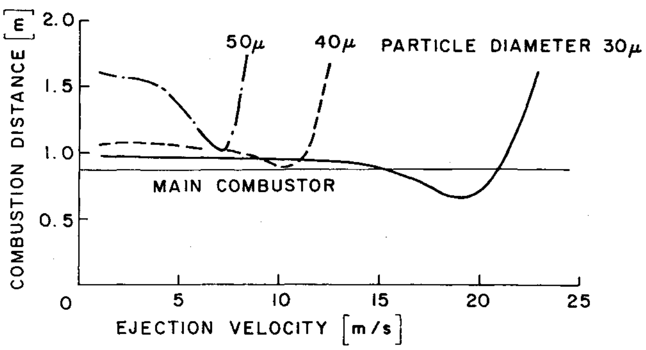

Fig. 3 Distance required for complete combustion of a boron particle when bypass air is added.

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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As a result of the difficulties involved in igniting and burning boron, numerous studies[3,4] aimed at determining the ambient conditions required for successful ignition (especially ambient temperature), ignition delay time, and burning rate for boron particles have been conducted. However, no attempt has been made to measure the surface temperature of boron during ignition and combustion.

The objective of this work is to demonstrate the successful use of infrared emission spectra from the burning surface of boron to deduce the burning-surface temperature. In deducing the burning-surface temperature, a two-color ratio pyrometry which offers the advantage of allowing temperature determination independent of the emissivity of the radiating object was adopted. The experiments, which involved determination of burning-surface temperatures of boron before achieving a full-fledged combustion, represent the first successful attempt to directly measure the burning-surface temperatures of boron. The burning-surface emissivity of the boron pellet was also determined.

Method of Approach

In this study, infrared emission spectra from the burning surface of a boron pellet in the postflame region of a flat-flame burner were measured with a Nicolet 740 FT-IR spectrometer. The burning-surface temperature was deduced from the measured infrared emission spectra by means of a two-color ratio pyrometry technique, which determines the temperature of a test object from the ratio of two measured radiances at two different wavelengths.

The method is similar to that used by Hottel and Broughton,[5] except that the present effort is devoted to the measurement of the burning-surface temperature of boron rather than flame temperature. In particular, two-color ratio pyrometry offers the advantage of allowing temperature determination independent of the emissivity of the radiating object. However, it must always be assured that the measured target is a near-gray body radiator for the two wavelengths in which the measurements are made, i.e., that the emissivity is independent of wavelength in the range of interest.

The spectral radiance from a burning surface is

$$L(\lambda) = \varepsilon(\lambda) \frac{C_1}{\lambda^5[\exp(C_2/\lambda T_s) - 1]} \tag{1}$$

where Planck's function for black-body radiation is used; λ is the wavelength, ε the emissivity of the burning surface of boron, T_s the burning-surface temperature, and C_1 and C_2 the first and second radiation constants. The ratio of any two measured radiances in different wavelengths, λ_1 and λ_2, can be calculated according to the following equation:

$$\frac{L(\lambda_1)}{L(\lambda_2)} = \frac{\varepsilon(\lambda_1)}{\varepsilon(\lambda_2)} \frac{\lambda_2^5}{\lambda_1^5} \frac{[\exp(C_2/\lambda_2 T_s) - 1]}{[\exp(C_2/\lambda_1 T_s) - 1]} \tag{2}$$

By assuming that the burning surface of a boron pellet is a near-gray surface, i.e., that emissivity is the same for λ_1 and λ_2, T_s can then be solved from Eq. (2) with measured $L(\lambda_1)$ and $L(\lambda_2)$.

In order to verify the near-gray surface assumption, the emissivities at four different wavelengths are calculated from Eq. (1) after T_s has been determined and compared. As discussed later in this note, it was found that the four emissivities obtained at four different wavelengths are almost the same, thus justifying the near-gray body assumption.

Figure 1 shows the schematic diagram of the experimental setup used in this study. Boron samples were prepared by pressing the amorphous boron powders (0.87 μm, SB Boron Corp.) into boron pellets with a diameter of 0.61 cm and length of 0.61 cm. During an experiment, the boron pellet was rotated 45 deg in order to obtain the emission spectrum from the bottom surface of the pellet rather than the side surface. To provide a test environment with uniform temperature and species concentrations, the boron pellets were located 10-mm above the burner surface. The burning-surface temperatures of boron pellets were measured under four different test conditions, as shown in Table 1. The flame temperatures and species mole fractions in the postflame region measured with quartz-coated thermocouples and a Varian 3700 gas chromatograph, respectively, are also given in Table 1. It should be noted that due to the low flame temperatures in the postflame region, the boron pellet did not achieve a full-fledged combustion.[2,6] Detailed descriptions of the measurement procedures and the flat-flame burner can be found in Ref. 7.

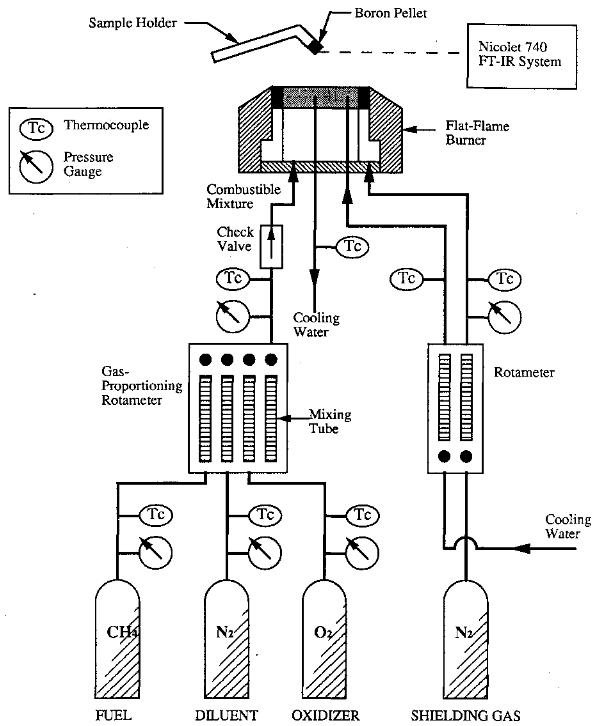

Fig. 1 Schematic diagram of the experimental setup.

Table 1 Test conditions for surface temperature measurements

No.	T_f,[a] K	Mole fractions, % O_2	N_2	CO_2	CO	H_2O
A	1758	5.49	64.53	9.51	0.46	19.66
B	1713	7.11	73.04	5.92	0.00	13.08
C	1593	13.95	65.53	7.60	0.00	12.04
D	1577	14.87	58.92	8.19	0.06	17.16

[a]Measured flame temperatures at 10-mm above the burner surface.

Results and Discussion

Figure 2 shows a typical emission spectrum measured by an FT-IR spectrometer from the burning surface of the boron pellet. As indicated in Fig. 2, no gas-phase emission was found in the wave number region from 2500 to 3200 cm^{-1} (3.125–4.0 μm); therefore, the radiances at four wavelengths (λ_1 = 3.66, λ_2 = 3.3, λ_3 = 3.45, and λ_4 = 3.85 μm) were used in calculating the burning-surface temperature.

The calculated temperatures and emissivities of the burning surfaces of boron samples in test conditions A, B, C, and D are summarized in Table 2. The surface temperatures were calculated from measured radiances at any two of four wavelengths by Eq. (2). The calculated values of emissivity from Eq. (1) were based on the surface temperature Ts_{12} obtained from measured radiances at λ_1 and λ_2.

The mean values of measured surface temperatures are in the range of 1095–1120 K at test condition A (T_∞ = 1758 K), 1089–1107 K at test condition B (T_∞ = 1713 K), 1054–1080

Table 2 Surface temperatures (K) and emissivities of boron samples under various test conditions[a]

	Test condition	Ts_{12}	Ts_{13}	Ts_{14}	Ts_{23}	Ts_{24}	Ts_{34}	$\varepsilon_1{}^b = \varepsilon_2{}^b$	$\varepsilon_3{}^b$	$\varepsilon_4{}^b$
A	Mean	1120.2	1118.3	1094.7	1108.5	1111.8	1095.7	0.845	0.846	0.848
	Standard deviation	11.7	22.0	9.6	41.8	6.8	33.6	0.032	0.031	0.030
B	Mean	1098.7	1092.3	1088.8	1107.0	1095.7	1094.3	0.841	0.840	0.841
	Standard deviation	10.4	20.7	20.3	20.7	2.9	19.5	0.029	0.029	0.027
C	Mean	1061.2	1079.7	1061.3	1074.8	1049.5	1053.8	0.756	0.756	0.759
	Standard deviation	15.4	23.0	18.7	18.3	8.4	19.2	0.042	0.041	0.041
D	Mean	1036.7	1043.4	1050.8	1050.2	1037.2	1037.0	0.797	0.798	0.797
	Standard deviation	12.9	15.9	20.0	16.0	7.9	13.9	0.041	0.043	0.040

[a]Mean values and standard deviations are obtained from six measured data at each test condition. [b]Emissivities are based on the surface temperature Ts_{12}.

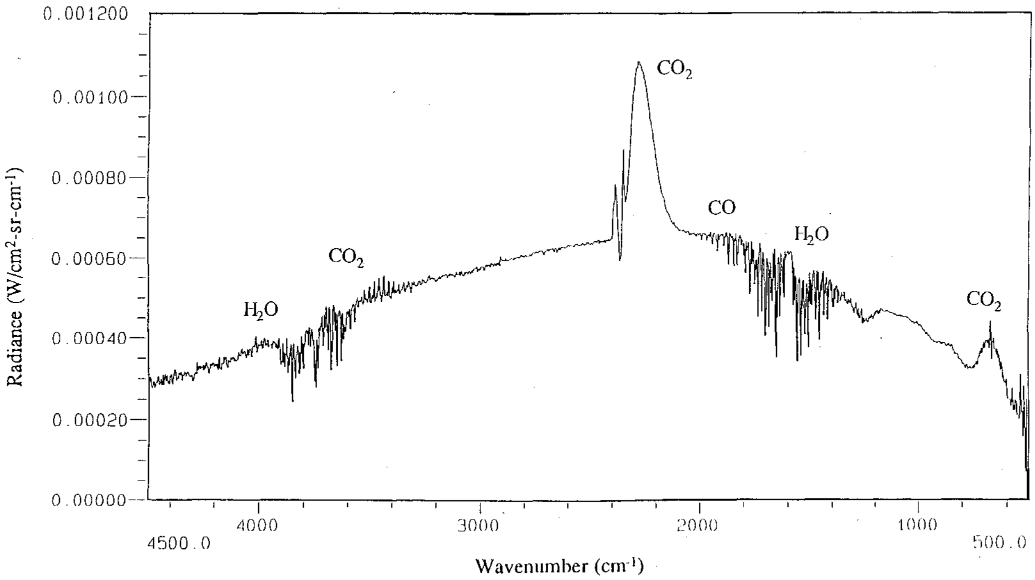

Fig. 2 Emission spectrum of the boron pellet at test condition A.

K at test condition C (T_∞ = 1593 K), and 1037–1050 K at test condition D (T_∞ = 1577 K). It is noted that the surface temperatures increase with increasing ambient gas temperatures. Basically, the surface temperature is determined by the energy balance between convective and radiative heat fluxes from the ambient, heat released from chemical reactions, and conduction heat losses from the surface to the cooler region. It is believed that the convective and radiative heat fluxes are much more dependent on ambient gas temperature than are other fluxes, and that these two heat fluxes increase with ambient gas temperature, thus causing the surface temperature to increase.

As far as the emissivity of the burning surface of the boron pellet is concerned (since the accuracy of two-color ratio pyrometry is primarily determined by the independence of emissivity at different wavelengths), it is essential to study the independence of the emissivity. The data given in Table 2 reveal good agreement between ε_1, ε_2, ε_3, and ε_4 in each measurement, thus justifying the gray-surface assumption for boron samples over the wavelength regime used. The emissivity differences are within 0.75%, which introduces a temperature difference of about 20 K.

Emissivity is generally not only a function of the wavelength and surface temperature, but also of the emission angle and surface condition. In this study, the emissivity of the boron pellet was found to be independent of the wavelength, and the emission angle was kept constant by fixing the sample holder at the same angle. Therefore, the parameters which affect emissivity in this study are surface temperature and surface condition. Comparing the emissivities of boron pellets at test conditions A, B, C, and D (see Table 2), some differences due to different surface temperatures and surface roughness are observed; in general, however, it can be concluded that the emissivities of the burning surfaces of boron pellets before full-fledged combustion are in the range of 0.75–0.88 when surface temperatures are between 1040–1120 K.

Summary and Conclusions

The temperature and emissivity of the burning surface of boron before full-fledged combustion have been successfully determined from the measured infrared emission spectra of the burning surface. The infrared emission spectra were measured with a rapid-scan FT-IR spectrometer system and analyzed with a two-color ratio pyrometry technique to deduce the burning-surface temperature of boron. The results of this study show that the emissivities of the burning surface of boron were constant in the wave number range of 2500–3200 cm^{-1}, and that the infrared emission within this wave number range can be used to determine the surface temperature of boron.

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