Direct Mixing and Combustion Efficiency Measurements in Ducted, Particle-Laden Jets

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Using water-cooled probes and hot-gas valves, gas-particle samples were withdrawn from the secondary duct of an air-augmented laboratory burner. Using a boron-loaded propellant, air/fuel ratio and secondary duct pressure were varied from 12/1 to 32/1 and from 82 to 127 psia, respectively. From sample analysis of chlorine, argon (air tracer), boron, and boron oxide, radial and axial profiles of air, gaseous fuel, particulate fuel and percent of boron combustion were determined. Particles and gases mixed at significantly different rates. Measured gas-phase mixing rates were comparable to model predictions, which assumed particles to be in equilibrium with gases. Boron combustion efficiency varied markedly with duct position, air/fuel ratio and secondary chamber pressure. Low boron combustion efficiency resulted principally from delayed ignition of the gaseous fuels after dilution by air reduced resulting gas-phase temperatures below the boron ignition temperature. This was especially true at low secondary duct pressures.

Introduction

MIXING and combustion of particle-laden jet streams with secondary airstreams are encountered in several important engineering applications, including rocket propulsion devices such as airbreathing rockets, jet pumps, tubular reactors, pulverized coal gasifiers, large-scale furnaces, and industrial stack effluents. This paper considers the specific application of air-augmented rockets. In these systems, fuel-rich solid propellants containing metals such as boron are burned in a primary chamber. The primary reaction products which contain the metal particles and unreacted gaseous fuels expand through a primary nozzle into a secondary chamber, where they mix and subsequently react with secondary air and then are exhausted through a secondary nozzle.

Such systems containing boron have shown decreasing boron combustion efficiency with decreasing secondary chamber pressure. It has been concluded from previous tests[1,2] that low boron combustion efficiency is caused by increasing difficulty in ignition of gaseous fuel/air mixtures with decreasing secondary chamber pressure in regions near the nozzle exit. When gas ignition does occur farther downstream, the local air/fuel ratio is too high to produce temperatures required for particle ignition. These observations have resulted from photographic observations and temperature measurements. Additional measurements of local properties in the duct were required to test this proposed mechanism.

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Index categories: Combustion in Heterogeneous Media; Jets, Wakes, and Viscid-Inviscid Flow Interactions.

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A generalized mathematical model for describing the mixing and combustion of particle-laden jets in confined ducts has been developed and computerized.[3,4] However, no definitive experimental data were available to provide a direct evaluation of this model. An extensive literature review of previous research in the area of ducted, particle-laden systems[5,6] was conducted. However, only limited data have been reported for mixing of reacting, or nonreacting, particle-laden systems. While extensive testing of air-augmented combustors has been conducted, resulting static pressure and thrust data are not sufficiently specific for definitive model evaluation.

Consequently, a series of nonreactive and reactive experimental tests have been conducted to provide basic data for model evaluation and for physical interpretation of combustion and mixing in ducted, two-phase flows.

The objectives of this study were: 1) to measure secondary air/primary fuel ratios as a function of radial and axial position in the secondary duct of a reacting, air-augmented laboratory jet, in order to determine the rate of mixing of gaseous components in the reacting, particle-laden system; 2) to measure total boron concentration profiles as a function of radial and axial position in the secondary duct in order to determine the rate of particle mixing in the reacting system; 3) to measure the amounts of combusted and uncombusted solid boron particles in order to determine directly the extent of particle combustion; 4) to compare experimental results with previous measurements and postulated mechanisms and with model predictions for particle-laden jets.

Related Work

Previous publications have reported detailed summaries of research related to air-augmented combustion processes.[1,2,5–7] The review will not be repeated here. However, specific work published by the authors relating directly to this study is briefly summarized.

Combustion Model

Development of a generalized model for describing mixing and combustion of a turbulent, compressible, particle-laden, confined, subsonic jet has been presented previously.[3,5] Initial model development[3] assumed the particle/gas mixture to be in

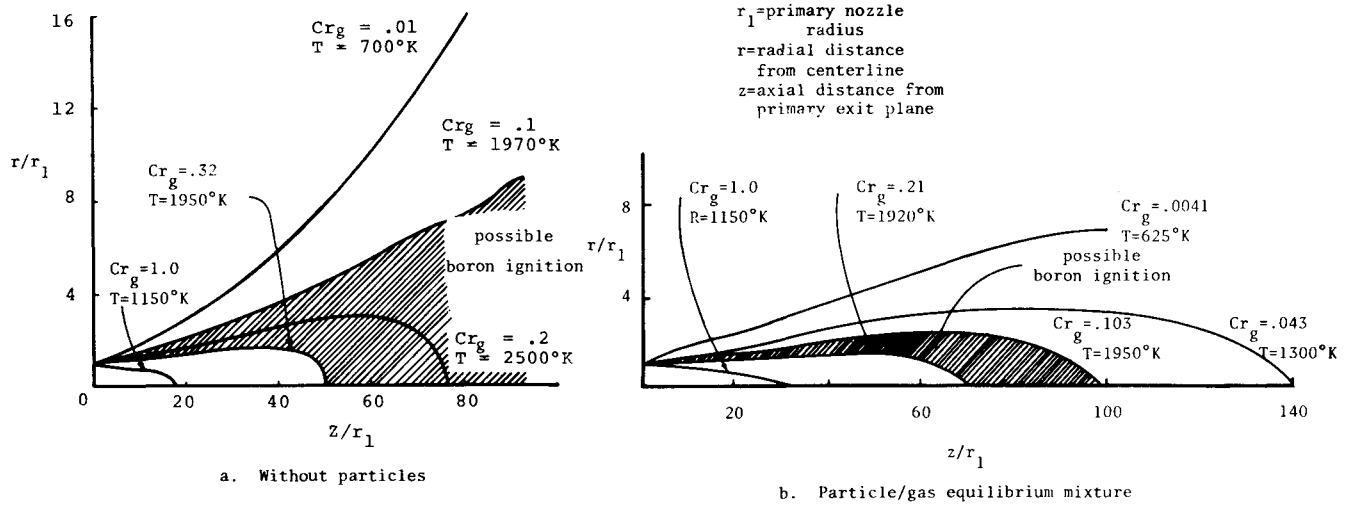


Fig. 1 Confined jet structure for case 1 from model predictions.

dynamic equilibrium while a particle ignition temperature could be specified. A subsequent model included estimates of particle drag while assuming gaseous species to be in local equilibrium.[4]

Also included were axial pressure gradient and wall shear stress effects. The model can consider a wide range of primary fuel and secondary oxidizer compositions.

Model predictions for the conditions experimentally studied in the test program are shown in Fig. 1. A major feature of the model predictions are the lines of constant weight fraction of primary exhaust in an exhaust/secondary air mixture. Associated with each of these lines is a specific temperature, velocity, and percent of metal burned. A very strong test of the model accuracy would therefore be a determination of the over-all weight percentage of exhaust or air at various positions in the duct. The experimental program discussed below was designed to provide this, and related information.

Boron Combustion Mechanism

Experiments with boron[8] showed that an initial particle temperature of approximately 1950°K is required for rapid boron combustion. However, gas temperatures in this range are apparently not produced in air-augmented systems when the combustion efficiency is low. Since the flame temperature of typical boron propellants in the primary motor is below 1950°K, efficient boron combustion must be dependent on the particle temperature rise produced by the combustion of the excess gaseous fuel (i.e., gaseous fuel such as H_2, and CO not burned in the primary chamber) with air in the secondary chamber. Theoretical calculations of the coaxial mixing process show that near-stoichiometric mixture-ratios exist in the beginning of the mixing process (near the primary nozzle). However, experiments with typical boron-containing propellants[1,2,9] showed that low boron combustion efficiency resulted when no significant gaseous fuel reactions occurred in these regions. When gaseous fuel reactions were finally initiated farther downstream in regions with higher air-to-fuel ratios, the gas-phase combustion temperatures were too low to initiate vigorous boron combustion. For the improvement of the combustion efficiency, provisions for achieving instantaneous gas-phase reaction in the beginning of the mixing region have to be made. However, in order to sustain these resultant high gas-phase combustion temperatures long enough to initiate stable boron combustion, the mixing rate has to be kept low. In fact, tests with conventional mixing and flame-holding aids (increased mixing rates near the fuel inlet) showed that these devices are of no advantage for the ignition and combustion process of boron particles in ducted rockets.[7,10] The experimental program described in this paper has been designed in part to confirm this postulated mechanism for low boron combustion efficiency.

Experimental

Test Facility

The experimental work was conducted at a test facility designed and constructed at the Naval Weapons Center. Previous work[1,2] at this lab. used a square configuration in both the primary and secondary ducts. For this study, new forward and aft-cylindrical sections were designed and built for the combustion test facility. These sections are shown in a schematic of the test facility (Fig. 2). The experimental program was designed so that sampling was conducted at only one axial position for a specific test. Thus, three tests were required to obtain an axial profile for a given test condition. Four sampling probes, placed at various radial positions, were used to obtain a radial profile at each axial position. Because the secondary cylindrical ducts obstructed photographs taken through the quartz windows, aft-cylindrical sections were not used for tests in which the probes were mounted nearest the nozzle exit plane. For these tests, plates were inserted in the top and bottom of the square section to give a 4-in. by 6-in. rectangular configuration in order to avoid recirculation and minimize differences in secondary duct cross-sectional area among tests.

Instrumentation

Static pressure and temperature measurements were made in order to determine the important test conditions. Motion pictures were taken for the tests in which aft-cylindrical sections were not used. The photographic techniques are outlined in Ref. 2.

Because of the high temperatures in the secondary duct and the importance of maintaining free particle flow while sampling, it was necessary to develop a special sampling system. The major equipment consisted of water-cooled sampling probes and free-flow valves which were developed and fabricated at Brigham Young University and are discussed below.

Sampling probes

The probes were made from $\frac{3}{8}$-in. o.d., stainless steel tubing with a $\frac{1}{8}$-in. o.d., stainless steel sample port. Four $\frac{3}{32}$-in. o.d., stainless steel tubes were also placed in the annular space between the $\frac{3}{8}$-in. o.d. shell and the $\frac{1}{8}$-in. o.d. sample port. The probe referred to as the centerline probe was displaced from the duct centerline by 0.1 in. A photograph of a typical probe before and after assembly is shown in Fig. 3. The four $\frac{3}{32}$-in. o.d. tubes carried the cooling water up to the probe tip. The water then flowed back through the probe in the remaining space between the outer shell and the sample port. Small holes were drilled in the outer shell near the probe surface. The probes used in this study were not designed to sample isokinetically because the laboratory burner tests lasted only 4–5 sec.

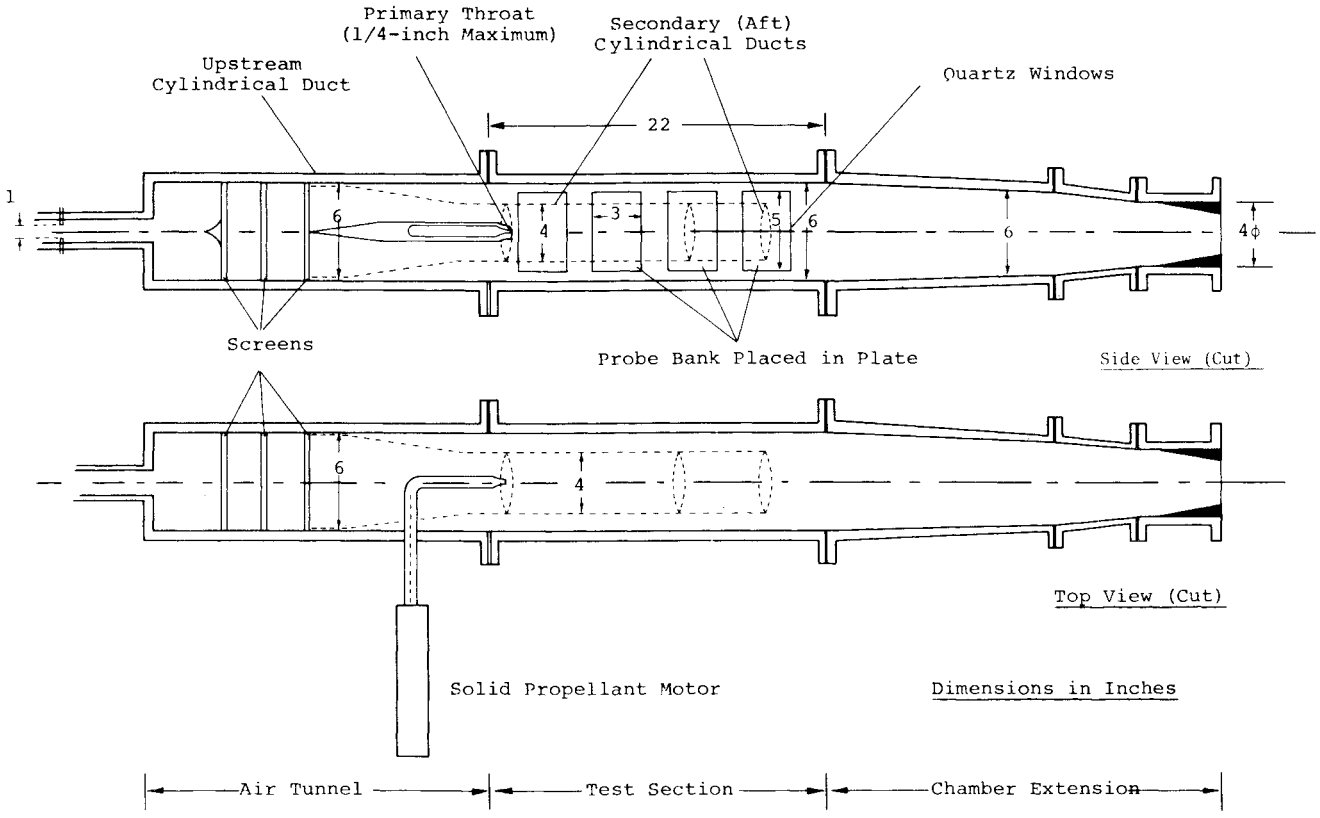


Fig. 2 Schematic of experimental test section.

Valve and sampling sequence

In order to avoid sampling during the ignition and decay transients of the firings, an electrically-controlled, air-operated, three-way spool valve was designed and developed. The valve was used either to direct the sample flow into the sample collection tank or exhaust the sample flow. The valve was operated so as to collect a particle/gas sample only during the steady portions of the rocket operation. With the sample isolated in the collection tank, water was injected into the sample and the tank was agitated to insure that all water-soluble materials were collected in the liquid phase.

Analytical Procedures

The objectives of the sample analysis were to determine primary fuel/secondary air ratios at various points in the secondary duct, and the concentration of boron and boron oxide at these same points. Knowing the fraction which key components comprised in the primary and secondary streams, the ratio of the key components in a sample established the secondary air/primary fuel ratio. The two key components used in the analysis were argon (Ar) tracer in the air and chlorine (Cl) in the propellant. Argon was chosen as the tracer because of its resistance to chemical reaction and its nearness in molecular weight to the normal components of air.

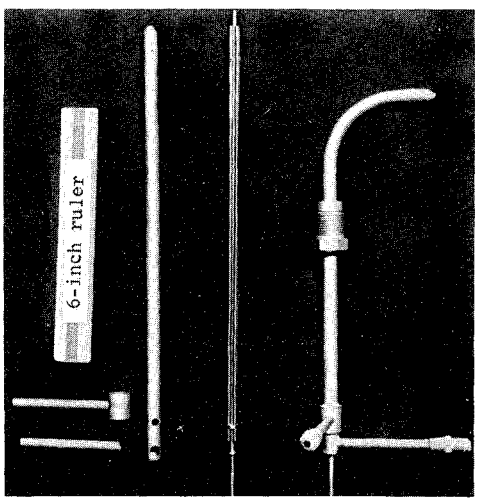


Fig. 3 Water-cooled sampling probes.

Argon

The quantity of argon within a sample was found by determining the quantity of gas sampled and then measuring the argon percentage of the gas with a mass spectrometer. The quantity of gas sampled was found by measuring the pressure in the sample tank after water had been injected and the samples allowed to equilibrate at room temperature. The gas volume was determined by difference from the liquid volume which was subsequently evaluated in the analytical procedure. The total number of gas moles was then determined using equation-of-state relationships.

Chloride ion

After the gas analysis was completed, the containers were opened, and the volume of liquid was measured. The solution was heated to insure that all the combusted boron (B_2O_3) was in solution, and the remaining solids were filtered. Aliquot portions of the filtrate were then used for the liquid phase analysis. Chlorine is combusted principally to highly water-soluble hydrochloric acid, forming the chloride ion in solution which was evaluated using Volhard titration techniques, which gives acceptable accuracy in acidic solutions.

Boron oxide

The quantity of B_2O_3, which was in the liquid phase as boric acid, was determined using titration techniques with mannitol.[9] Mannitol combines with weakly acidic boric acid to

form a relatively strong acid complex that can then be quantitatively titrated with potassium hydroxide solutions. Under these conditions, only one hydrogen ion from the boric acid complex is neutralized.

Boron

The filtered solids were oxidized in a concentrated solution of hydrochloric acid, nitric acid, and sulfuric acid. Under these conditions, the unburned boron is oxidized to boric acid. The acidic solution was then neutralized to the normal pH of a dilute boric acid solution, which precipitated aluminum as the hydroxide. Mannitol was added, and the solution was titrated with KOH as in the analysis of B_2O_3. This procedure is also reported in Ref. 9.

Gas composition

The gas composition was determined with a gas chromatograph for tests at two conditions in order to study the extent of combustion in the gaseous fuel. Species measured included O_2, CO, CO_2, CH_4, and H_2.

Test Program

The test program is outlined in Table 1. All of the tests were conducted with a solid propellant containing 50 weight percent of boron, 4 weight percent of aluminum, 25 weight percent of ammonium perchlorate, and 21 weight percent of a rubber binder. Propellant grains were developed and fabricated by Atlantic Research Corp. under contract from the Air Force Rocket Propulsion Lab., Edwards, Calif.

Chromatographic analyses were made at the front axial station for Case 1 and the middle axial station for Case 4. Vitiated air temperature was 540°K while the secondary throat diameter was 1.1–1.6 in. The argon weight percent in secondary air was 5%.

Table 1 Experimental test program and test conditions

Case	Average primary chamber static pressure	Average secondary duct static pressure		Air/fuel wt ratio
		Air only	Air/fuel mixture	
1	190 psia	70 psia	127 psia	19
2	200 psia	70 psia	84 psia	32
3	275 psia	40 psia	82 psia	12
4	57 psia	20 psia	25 psia	19

Test Results

Sample analysis

Table 1 summarizes test conditions for the four test cases. Experimental data obtained from probe sampling and subsequent analysis for the first three conditions are summarized in Table 2. Properties reported are: 1) the chlorine/argon ratio; 2) the percent of total boron combusted to B_2O_3, which was obtained from elemental boron and B_2O_3 measurements; 3) the total boron $(B+B_2O_3)$/chlorine ratio.

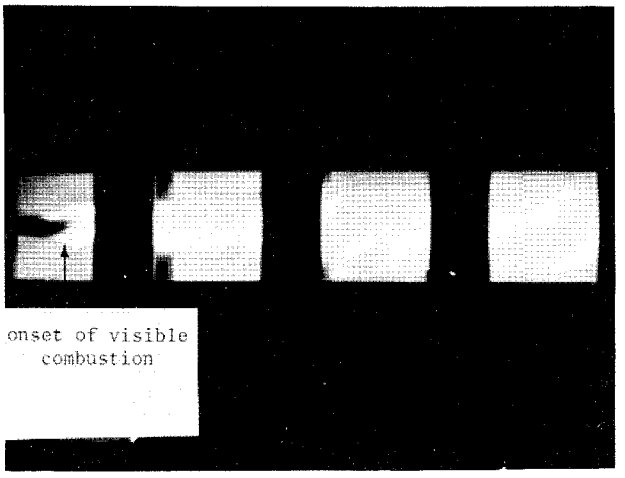
Gas chromatograph

The movies showed that the gas samples for gas chromatographic analysis were taken upstream from where gaseous plume ignition occurred. The analysis of these samples showed significant fractions of both secondary oxidizer (oxygen from the secondary air) and uncombusted gaseous fuels (hydrogen, carbon monoxide, and methane).

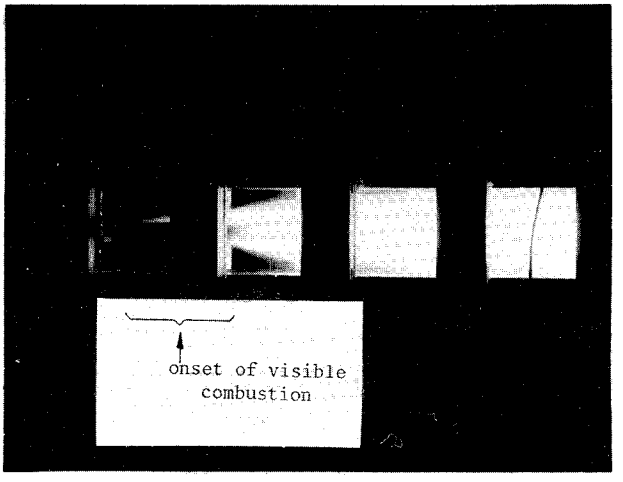
These findings support the observation that excess gaseous fuel did not react appreciably in the mixing region upstream of the plume flame.

Photographic observations

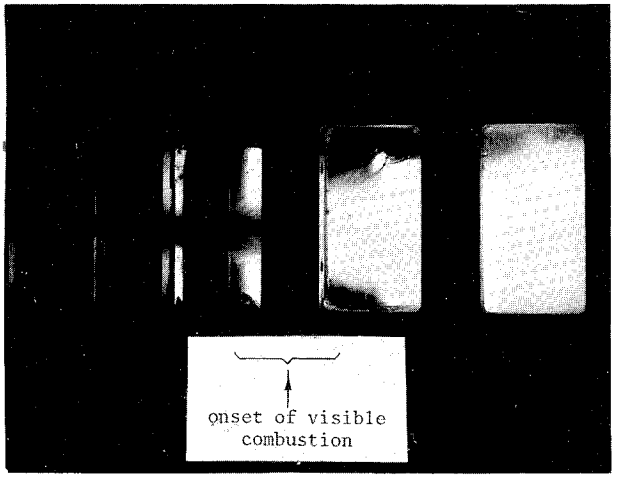
Figure 4 shows plume reaction zones with the primary nozzle



a) Case 1, High Secondary Duct Pressure



b) Case 3, Intermediate Secondary Duct Pressure



c) Case 4, Low Secondary Duct Pressure

Fig. 4 Photographs of plume combustion characteristics at various secondary chamber pressures.

on the left and the secondary nozzle (not shown) on the right. The position of the onset of plume inflammation is identified as the transition from black mixing zone to luminous flame and is reproducible for a specific set of test conditions.[9] For test conditions with a high secondary chamber pressure (case 1) and low air-to-fuel ratio, plume inflammation occurred about $1\frac{1}{2}$ in. (middle of first window in Fig. 4a) downstream from the primary nozzle and was followed by a brilliant white plume further aft in the duct. For test conditions with a lower initial secondary chamber pressure (case 3), the site of plume inflammation shifted downstream to 5 in. from the primary nozzle (beginning of second window) in Fig. 4b. For tests with an even lower secondary chamber pressure (case 4), plume inflammation was 7 in. from the primary nozzle (end of second window) in Fig. 4c and was followed by a yellowish, radiating plume. At high pressure and high air-to-fuel ratio (case 2), plume inflammation did not occur.

Data Analysis

Reproducibility

Average test conditions among runs used to obtain axial profiles were summarized in Table 1. In general, the deviation of the test conditions for a set of runs required to give a complete profile was less than $\pm 10\%$ of the average value. There was some difficulty in maintaining a constant primary chamber pressure throughout a complete sampling period during a specific test. The reported primary chamber pressures for each test are the average pressures during the sampling period. The deviations of the primary chamber pressure during the sampling period for a specific test ranged upwards to $\pm 15\%$ of the average value.

The test for case 1 at the axial position farthest downstream from the primary nozzle was duplicated in order to evaluate the reproducibility of the sampling and analytical techniques. The evaluation of primary gas fraction varied by a maximum of $\pm 6\%$. The reproducibility was best near the centerline where the quantity of primary fuel in the sample was larger. The percent of boron combustion varied by a maximum of $\pm 6\%$ of the average value, and the B/Cl mole ratio varied by a maximum of $\pm 14\%$ of the average value.

For case 1 at the third axial station, the sample from the position second closest to the centerline was taken with the sample tank initially filled with nitrogen to one atmosphere. All the other tests were taken with sample tanks which were initially evacuated. The reproducibility at this sampling position was not significantly different from the reproducibility of the samples in which the tanks were evacuated for both runs.

Consistency

The test results which were summarized in Table 2 show several basic trends which were evident in all three test conditions investigated. There was a consistent decay of the primary gas fraction in the radial direction for all axial positions, and a consistent decay of the near-centerline primary gas fraction with increasing distance downstream of the primary nozzle exit. There was a consistent increase of percent of boron combustion in the axial direction for samples taken from near the centerline. The ratio of boron oxide to boron also consistently increased with radial distance from the centerline. This does not necessarily imply that combustion efficiency of boron is high in regions of high B_2O_3/B ratio, since the outer regions are very dilute in total boron, and since mixing rates of the metal and oxide may differ. The B/Cl mole ratio of the solid propellant is about 22. The B/Cl mole ratio should not be always greater (or smaller) than the value for the primary fuel at all radial positions for a given axial position. However, the front axial position for case 3 had B/Cl mole ratio values greater than 22 for all the samples which contained B or Cl from the primary fuel. The aft positions for case 1 had B/Cl mole ratio values less than 22 for all the samples containing B or Cl. This could result from asymmetric effects in the duct. All the other axial positions of the three tests had B/Cl mole ratio values from the radial positions which ranged above and below 22. The axial position nearest the primary exit plane for case 2 is not reported because of difficulty in reproducing the conditions of the tests that existed at the other two axial positions. The tests at these latter aft-positions had negligible secondary combustion and a relatively small pressure in the secondary duct. There was significant secondary combustion during the test where sampling was done at the position closest to the primary exit, possibly induced by the probes.

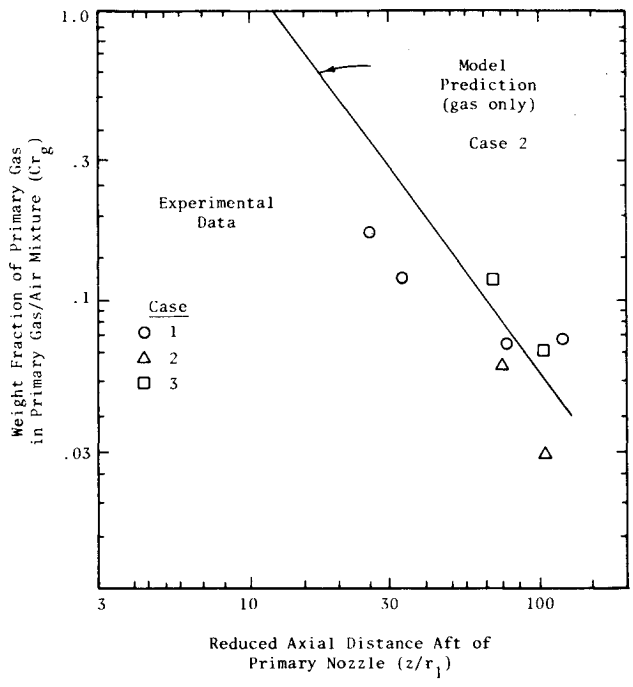
Particle Mixing

Model predictions have been based on the assumption that the primary particles and gases mix at the same rate throughout the duct. Since Cl is present in the secondary chamber principally as gaseous HCl, Cl is representative of the way in which the gases from the primary fuel mix relative to the particles. If the primary gases and the primary particles mixed at the same

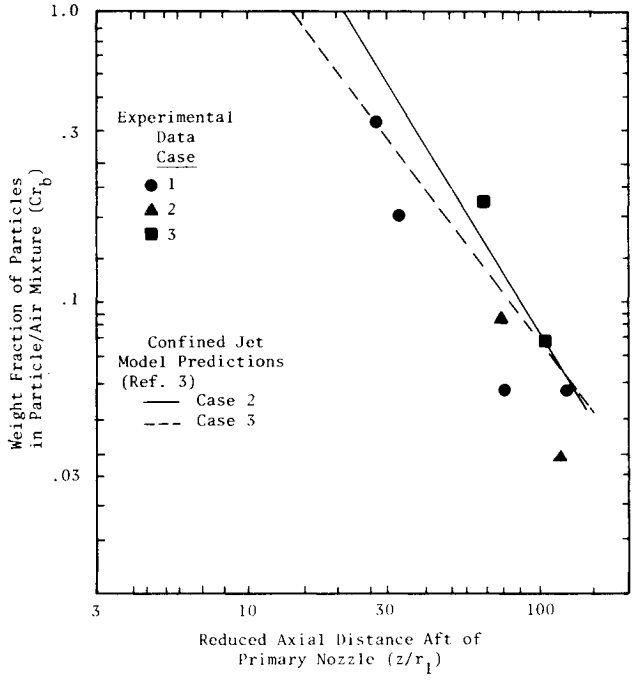
Table 2 Summary of test results

Test case	r,[a] in.	Test results $z^b = 3.19$ in.			$z = 7.63$ in.			$z = 12.19$ in.		
		Ar/Cl[d]	B_2O_3/B[e]	B/Cl[f]	Ar/Cl[d]	B_2O_3/B[e]	B/Cl[f]	Ar/Cl[d]	B_2O_3/B[e]	B/Cl[f]
1[c]	0.10	2.2	0.13	29	4.6	0.28	13	4.7	0.48	14
	0.47	4.1	0.22	9.1	6.5	0.37	7.7	5.6	0.52	10.5
	1.06	∞	NPF[g]	NPF[g]	27	0.70	3.9	15	0.71	5.0
	1.58	∞	NPF[g]	NPF[g]	∞	NPF[g]	NPF[g]	40	0.87	3.5
2	0.10				6.1	0.14	33	13	0.18	22
	0.47				12	0.22	14	18	0.18	17
	1.06				2000	1.00	10	92	0.60	3.8
	1.58				∞	NPF[g]	NPF[g]	∞	NPF[g]	NPF[g]
3	0.10	1.3	0.12	51	2.4	0.14	38	5.1	0.26	22
	0.47	1.6	0.12	41	4.2	0.20	22	5.0	0.30	17
	1.06	64	0.80	29	52	0.70	3.1	15	0.47	7.0
	1.58	∞	NPF[g]	NPF[g]	∞	NPF[g]	NPF[g]	37	1.00	2.3

[a] r is radial distance from centerline of secondary chamber.
[b] z is axial distance from primary nozzle exit.
[c] Data reported for test case 1 at $z = 12.19$ in. is average of 2 tests.
[d] Ar/Cl is mole ratio of Ar/Cl.
[e] B_2O_3/B is ratio of B as B_2O_3 to total B.
[f] B/Cl is mole ratio of total B to Cl.
[g] NPF refers to samples in which neither primary fuel component (B, Cl) was detected.



(a) Gases, reactive (equilibrium)



(b) Particles, assuming aluminum and 6% boron reactive (equilibrium)

Fig. 5 Comparisons of experimental and predicted centerline rates of decay for gases and particles.

rate, the B/Cl mole ratio would be uniform throughout the duct. However, since the B/Cl mole ratio (Table 2) consistently decreases with radial distance from the centerline, there is strong indication that the primary fuel gases mix more rapidly in the radial direction than the primary particles. Figure 5 also shows slower initial centerline decay of particles than gases, further confirming particle drag effects. Because the initial decay of particles lags that of the gases, and because particles and gases must reach the same final state, it is no surprise that the slope of particle decay is greater than that for the gases. However, the value of this logarithmic slope is not a function of mixing rate, but depends principally on density ratio.[11] According to Ref. 6, the mixing coefficient is proportional to the core length; from this observation it is estimated from Fig. 5 that initial mixing of the particles occurs at about 0.7 times the rate that of the gases.

Gas Mixing

Model predictions have been made for test cases 1–3 assuming particle/gas equilibrium.[3] The model predicts the distribution of weight fraction of gaseous exhaust (Cr_g) which can be compared directly with experimental measurements. In this case, it was assumed that the propellant contained no boron or aluminum, leaving principally gaseous species. Test results showed more rapid mixing of gases than particles in regions near the primary nozzle. This caused separation of gaseous fuels from particles, and gases proceeded to mix somewhat independently of the particles. Figure 5a shows a comparison of all gas weight fraction measurements nearest the centerline with the results predicted by the model. The model predicted very small differences in mixing for the three test conditions. The experimental data from all three tests also show only minor differences, confirming this prediction. The measured gas mixing rate is also comparable to that predicted by the model as shown in Fig. 5a. Figure 5b compares predicted and measured centerline particle decay rates. In this prediction, the entire propellant formulation was used and it was assumed that 6% of the 50% of boron reacted in the primary motor. This value corresponds with the data nearest the primary nozzle as shown in Table 2. Predicted particle decay rates are also in good agreement with measured data.

Figure 6 shows predicted and measured radial gas and solid composition profiles at each axial station for case 1. These data also confirm that gas mixing is taking place more rapidly than particles and comparable to predicted levels except nearest the exit plane. This observation was similar in each of the other two test cases which were compared with theory.

Air/Fuel Ratio

As summarized in Table 1, the only significant difference in initial test conditions between case 1 and case 2 was the over-all air/fuel ratio. As shown previously in Fig. 5, there was no significant difference in the mixing rates for all 3 test conditions for which profiles were obtained. However, the data of Table 2 shows higher percentages of boron combustion near the centerline at the lower over-all air/fuel ratio (case 1), which also resulted in a higher secondary chamber pressure. The observation of improved combustion at lower air/fuel ratios is also supported by the photographic observations.

Secondary Chamber Pressure

Although the effects of initial secondary chamber pressure could not be completely isolated, the test cases show that boron combustion is better for conditions with higher initial secondary chamber pressures with similar air/fuel weight ratios. Results from tests with high initial secondary chamber pressures (case 1) showed that for samples nearest the centerline, boron combustion increased from 13% at the beginning of the secondary duct to 48% at the aft sample station. For a lower pressure condition (case 3), boron combustion only increased from 12% to 26% in the same distance.

Boron Combustion Efficiency

Efficient boron combustion depends upon a gas-phase flame with a local temperature in excess of the ignition. temperature of boron. Using experimental measurements of local gaseous fuel/boron/air and assuming boron to be inert, local gas flame temperatures were calculated and are shown in Fig. 7. These calculations included the measured effects of nonuniform particle and gas mixing. The temperatures calculated are stagnation

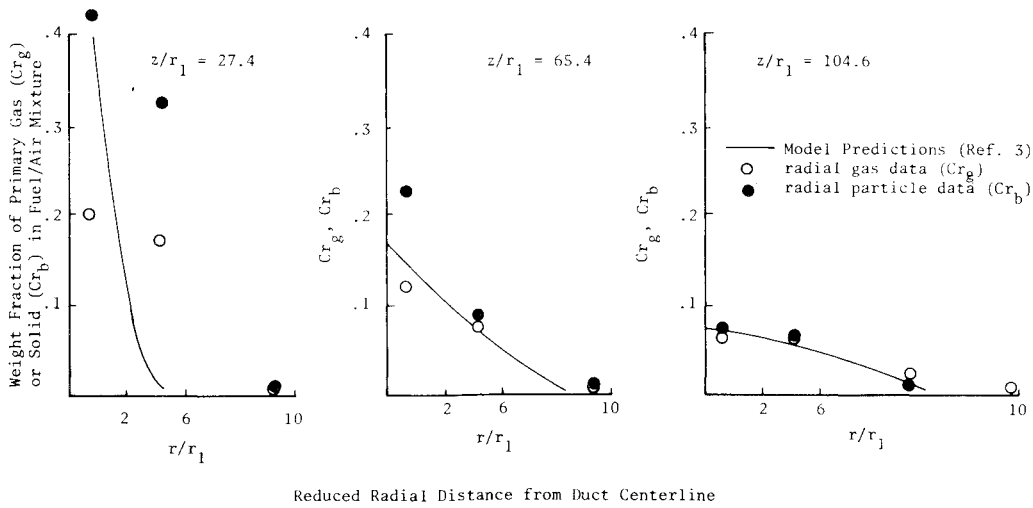


Fig. 6 Comparison of experimental gaseous and particle radial profiles with model predictions (assuming aluminum and 6% of boron reactive), case 3.

temperatures which are somewhat higher than the actual temperatures in high velocity plumes, especially near the centerline. The diagram indicates that gas-phase temperatures exceed the boron ignition temperature of 1950°K only near the primary nozzle. These temperatures will also exceed the maximum values that would result from a gas/particle mixture in equilibrium with 50% of boron, since the sensible heat losses to the inert boron will be less in the nonequilibrium case. If the excess gaseous fuel can ignite near the primary nozzle (case 1), then boron particle ignition and combustion can result from the high gas temperature (2400°K). Boron combustion in these local high temperature regions can contribute to high temperatures during the mixing process with the air until decisive ignition of the entire boron-laden plume is achieved. Consequently, the boron efficiency is relatively high as indicated by the test results of case 1. When gas-phase ignition occurs 5-in. downstream from the primary nozzle (case 3), boron combustion can only start in downstream regions where the maximum gas-phase temperatures are below the required boron ignition temperature. No vigorous boron combustion can be achieved, and the efficiency decreases as indicated in the case 3 at low secondary chamber pressure. Since both the model predictions and experimental results showed only small differences in the mixing structures for the three test conditions investigated, it is likely that the temperature profiles for case 3 are similar to that shown in Fig. 7.

It was previously noted that secondary chamber pressure had a significant effect on boron combustion and only a small effect on mixing structure. The photographic observations and predicted flame temperature profiles (based on inert boron) indicated that the boron particle temperature rise during the particle ignition process was considerably higher at conditions with increased initial secondary chamber pressure.

These results indicate that boron combustion efficiency is controlled to a large extent by whether the gases ignite and burn near the nozzle exit. If gas ignition is postponed until significant mixing has occurred, then local fuel/air ratios are too low to produce gas flame temperatures higher than the boron ignition temperature.

Boron ignition does not insure complete boron combustion.[4] Model predictions have been compared with boron combustion rates along the centerline in order to assess the boron combustion rate following ignition. Figure 8 shows a comparison of measurements and predictions from the model predictions which include boron particle nonequilibrium effects.[4] The theoretical computations, for the reported boron particle diameter in the fuel of 1–3 μ, are compared with samples taken near the duct centerline. The model predicts that combustion occurs at a somewhat faster rate than was experimentally measured. However, the experimental measurements only determined concentrations of one boron combustion product, B_2O_3. Figure 8 also indicates that the model seems to adequately predict regions in the jet where rapid boron combustion begins.

Conclusions

This study has reported results of detailed probe measurements in the secondary combustion chamber of an air-augmented

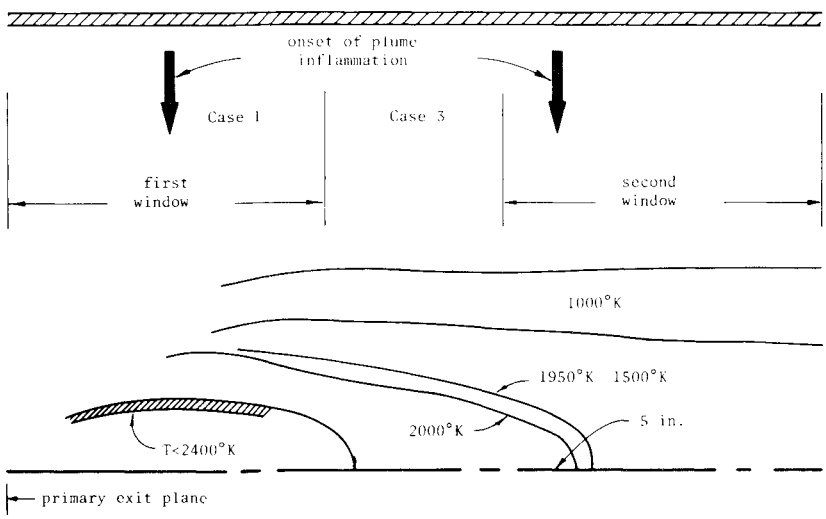


Fig. 7 Observed location of plume inflammation and temperature profiles deduced from experimental data.

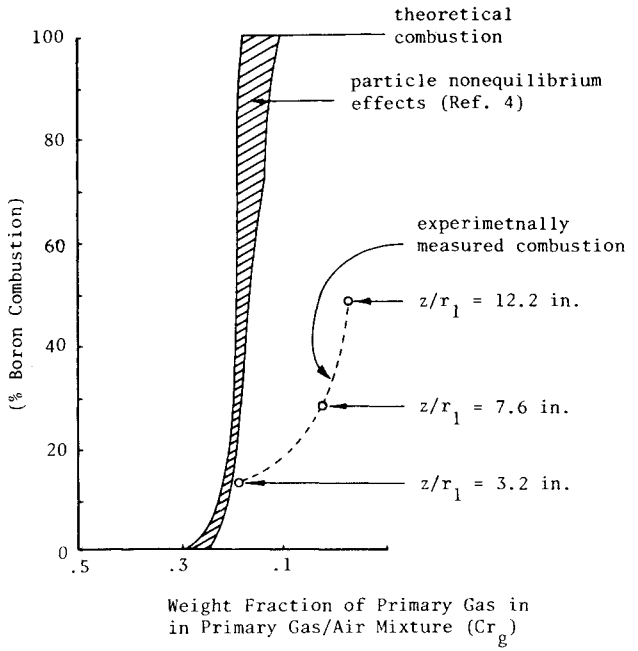


Fig. 8 Comparison of experimental and theoretical centerline boron combustion rates.

laboratory burner. These measurements have provided the radial and axial distribution of the percent of air, the percent of gaseous fuel, the percent of particulate fuel, and the percent of boron burned. In addition, photographic and chromatographic analyses of selected gas samples have provided additional information. Results of this study have produced the following significant conclusions:

1) The boron/boron oxide particles mix at a significantly slower rate than the gases. That is, the particles are out of dynamic equilibrium with the gases.

2) The gases and particles mix at a rate which is comparable to that predicted by the model.

3) The percent of boron combusted along the centerline decreased significantly with increases in air/fuel ratio. Photographs for the higher air/fuel ratio showed that the gaseous fuel did not ignite in the secondary chamber.

4) The percent of boron combusted along the centerline decreased with decreasing secondary duct pressure. At the same time, the location of the onset of combustion of the excess gaseous fuels in the secondary chamber moved farther aft of the primary nozzle exit plane with decreasing pressure.

5) A major reason for observed low boron combustion efficiency is the lack of significant burning of the excess gaseous fuels in regions near the primary nozzle exit plane where the resulting equilibrium gas temperatures would exceed the boron particle temperature of 1950°K necessary for rapid combustion. When ignition of the gases occurs in farther aft regions of the duct, the mixture is too diluted in air to reach 1950°K. This result implies that rapid, early mixing can be disadvantageous to promotion of high combustion efficiency.

6) This combustion mechanism for low boron combustion efficiency is in agreement with previous observations and conclusions.[1,2,9]

7) The results suggest that adequate prediction of air-augmented combustors must account for both particle dynamic nonequilibrium effects and gas kinetic nonequilibrium effects.

8) Results of this study have specific application to other types of high speed particle-laden flows.

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