# Boron Particle Nonequilibrium Effects in Combusting Ducted Flows

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## Theme

OPTIMUM design of air-breathing propulsion systems will require an adequate description of the mixing and combustion of ducted, fuel-rich, primary streams with secondary air. The primary stream will often contain metal particles such as boron, magnesium or aluminum. Development of a model has been previously reported[1,2] for describing combustion of a particle-laden jet which is mixing with a subsonic secondary air stream in a duct. This model considered the particles to be in dynamic and thermal equilibrium. This synoptic summarizes an extension of this earlier model to include particle nonequilibrium effects.[3] Particle drag, thermal lag, and particle ignition, melting, and combustion effects are considered. A series of parametric calculations for a typical boron-loaded, air-augmented system shows effects of particle size and secondary duct pressure on metal combustion efficiency. Methods of improving combustion efficiency at low pressure are briefly examined.

## Contents

The boron particle combustion process has been divided into heat-up, ignition, and combustion regions. It has been assumed[4,5] that boron particles ignite at a distinct particle temperature, which may be a function of pressure and composition. Following ignition, either by hot gas or by a laser, the particles emit a photographable light which may result from surface combustion of the boron and oxidizer.[6,7] A significant increase in the intensity of combustion is observed at the same time the particle changes from an irregular shape to a spherical droplet.[7] At closely spaced temperatures, the boron oxide boils and the boron particle melts. It has therefore been assumed that the ignition period of the boron continues to the boron melting point, after which steady combustion follows. For the combustion region, it has been assumed that the particle burnrate is diffusion-limited and takes place at least partly in the gas-phase surrounding the particle.[6]

Drag, heat-transfer, and combustion equations for boron particles were formulated for each of the regions described previously. Continuous variation in particle diameter during ignition and combustion periods is considered. Particles are assumed to be spherical, with uniform, temperature-independent properties, and temperature gradients within the particle are neglected as are interactions between particles. Only the steady-state process is considered and random particle motion in the turbulent medium is neglected.

The required equations for describing particle behavior have been reported in detail.[3] These equations include axial and radial components of particle motion, a particle energy balance, and particle fuel and gaseous oxidizer mass balances, in particle streamline coordinates for heat-up, ignition, and combustion regions. Auxiliary equations describing variations in the drag coefficient, mixture viscosity and conductivity, heat-transfer coefficient, and oxidizer diffusivity were also required. These equations have been programed for computer solution using standard integration techniques. The resulting solution provides prediction of the particle velocity components, thermal history, and particle consumption rate in the complex gas-phase structure.

In order to insure reasonable predictions of particle burn rates, experimental boron particle ignition and combustion data have been used to evaluate selected parameters. In the ignition region, the activation energy for surface reaction of oxidizer and fuel was taken to be near the heat of vaporization of liquid boron oxide,[6] and the pre-exponential factor ($Z'$), in the Arrhenius expression used to describe the temperature dependence of the reaction, was evaluated from 22 separate hot-gas, boron-ignition experiments[4,5] which included variation in particle diameter (34–49 $\mu$), gas temperature (1980–2870°K), and oxygen mole fraction (0.21–0.41). Pressure was one atmosphere. $Z'$ values were reasonably constant for all of these experiments, and were not a significant function of initial particle diameter, gas temperature, or oxidizer concentration. The average value of $Z'$ for these data was $(5.8 \pm 1.7)10^{10}$ cm/sec.

In the combustion region, where the combustion rate has been assumed to be diffusion-controlled, the average value of the ratio of flame diameter to particle diameter ($\bar{\delta}$) has been evaluated from 24 particle burn-time experiments[5-7] using the particle model equations. Particle diameter ranged from 34 to 75 $\mu$, gas temperature from 300 to 2870°K, pressure from 1 to 35 atm, and oxygen mole fraction from 0.21 to 1.0. Values for $\bar{\delta}$ for experiments at 1 atm were not a function of particle diameter, gas temperature or oxidizer concentration. However, $\bar{\delta}$ increases with pressure according to the equation: $\bar{\delta} = (2.07 \pm 0.4) + 0.05p$, where $p$ is the total pressure (atm).

Using the existing confined jet model,[1,2] jet structures were made for typical air-augmented rockets operating at high and low pressures. For most computations, the solid propellant contained 50% (weight) boron, 22% ammonium perchlorate, and 28% rubberized binder, while chamber pressure was 1000 psia. For the gas-phase structure, the boron particles were assumed to be inert, which provides a conservative environment for predicting heat-up, ignition and subsequent combustion of the metal particles. Using this predicted gas structure in the duct, particles of various sizes have been tracked from the primary nozzle exit plane to the end of the secondary duct, or until they were consumed through combustion. Particle initial diameters of 4–20 $\mu$ were considered. These particles were released at the primary nozzle exit plane at various radial positions. It was assumed that the boron was inert at the nozzle exit, since predicted gas temperatures in the combustion chamber were in the range of 1000°K. However, the gas temperature increases in the secondary duct from combustion of gaseous fuels in the primary exhaust ($CO$, $H_2$) with the secondary air. The initial radial component of the gas velocity was determined assuming a point-source

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Index categories: Combustion in Heterogeneous Media; Subsonic and Supersonic Airbreathing Propulsion; and Reactive Flows.

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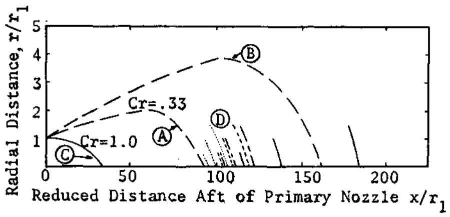


| | Fig. 1 | Fig. 2 |
|---|---|---|
| Air Velocity (ft/sec) | 100 | 100 |
| Air Temperature (°K) | 714 | 485 |
| Initial Duct Pres. (psia) | 280 | 14 |
| Duct Length (ft) | 11 | 22.6 |
| Primary Nozzle Radius (ft) | 0.146 | 0.146 |
| Duct Diameter (ft) | 2 | 2 |

....end of heat-up
----end of ignition
–·–end of melting
——particle consumed

(D)
short line = 5μ
medium line = 10μ
long line = 20μ
$C_r$ = weight fraction of primary jet

(A) Particle Equilibrium Ignition
(B) Particle Equilibrium Extinguishment
(C) Core

**Fig. 1 Effect of particle size on predicted heat-up, ignition, melting and combustion of boron particles in a confined duct at high pressure.**

flow through a primary nozzle whose divergence half-angle was 15°.

The onset of ignition was assumed to occur at a particle temperature of 1850°K while boron oxide boiling occurred at 2316°K and boron particle melting and subsequent diffusion-controlled burning was initiated at a particle temperature of 2450°K. A summary of the initial conditions and selected predicted parameters for these particle nonequilibrium computations is given in Ref. 3 together with the results. Only two cases are discussed below.

For the high-pressure case (280 psia), the results of the nonequilibrium computations are illustrated in Fig. 1. For particles in the range of 4–20 $\mu$, heat-up and subsequent ignition were predicted to occur soon after the particles encountered gas temperatures in excess of 1850°K. The particles were generally consumed in the hot-gas region, and in each case, particle combustion was complete prior to the exit of the confined duct. The heat-up, ignition and melting steps occurred most rapidly while steady particle combustion required the bulk of the time. While the large particle sizes showed increased lag during the combustion process, even the largest particles considered were predicted to be consumed inside the secondary duct. According to these predictions, only 6–12% of the particle mass was consumed during the ignition and melting phase.

For low pressure (14 psia), results are illustrated in Fig. 2. A longer duct was required to show any significant features. The particles near the duct centerline do not reach a sufficiently high gas temperature until a duct length of 17.5 ft was reached. Upstream of this point, the bulk of the particles were located in regions where the gas temperature was too low for ignition. Particles less than 20 $\mu$ ignited shortly after the gas temperature reached 1850°K, indicating sufficiently rapid heat-up at the lower pressures. However, the particles were unable to self-heat above about 2000°K and the ignition step was never completed. During this latter period, less than 2% of the particle mass was consumed prior to exhausting from the duct.

Simmons and Baumann[8] have recently shown heat-up, ignition, melting, and combustion data for 0.5–4 $\mu$ particles in a shock

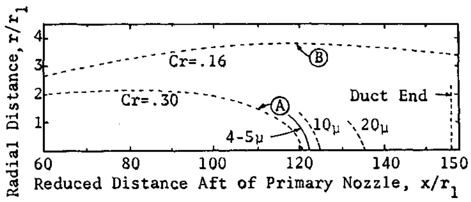


**Fig. 2 Effect of particle size on predicted heat-up and ignition of boron particles in the aft-regions of a confined duct at low pressure.**

tube at 10 atm pressure and with a gas temperature of 2000–2230°K. These authors reported that calculated times for heat-up, melting and combustion of 0.5–4 $\mu$ boron particles at 10 atm were less than observed values by a cumulative factor of 2–3, which indicates that the boron may burn even less readily than predicted above. These small particles were also observed to ignite at a gas temperature of 2000°K (9.4 atm), but did not reach the steady combustion phase prior to extinguishment, which was also the behavior predicted above.

The poor combustion efficiency at low pressure is caused by slow jet/air mixing discussed previously and by particle nonequilibrium effects. Self-heating by surface reaction at the lower pressure in the presence of a gas at 2040°K was not sufficient to ignite and melt the particles.

The model outlined above provides a tool for evaluating possible techniques for improvement in combustion efficiency at low pressures and at high pressures. Among the possible techniques for improving combustion efficiency are: a) enhancement of turbulent, jet/air mixing rates; b) use of more easily ignitable metals, such as magnesium; c) reduction in chamber pressure, with subsequent reduction in jet velocity; d) higher secondary duct pressures; e) increase in primary propellant oxidizer percentage; and f) use of high air/fuel ratios.

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