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ORIGINAL ARTICLE

A study of solid ramjet fuel containing boron–magnesium mixtures

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Abstract Solid fuel ramjets (SFRJ) are known for their operational simplicity and high specific impulse. The performance of the SFRJ propulsion system is directly tied to the energy density and combustion behavior of the fuel. A typical solid fuel used in a ramjet application is a collection of metal particles suspended in a polymeric binder. Boron is the ubiquitous candidate when considering metal additives for fuels due to an impressive 122.5 kJ/cm^3 energy density. However, boron requires long residence times in combustors due to its high melting and boiling points. Magnesium appears to be a natural complement to boron; while possessing a lower energy density (42.1 kJ/cm^3), it burns with a high flame temperature and readily reacts in combustion with a low melting point. In this study, several HTPB–boron–magnesium fuels are studied on a small scale to evaluate performance for ramjet application. Holography experiments are conducted, as well as laser ignition tests, to study particle behavior just above the fuel surface. Small, center-perforated fuel grains are examined in a direct-connect SFRJ test stand configuration to measure ignition temperatures and performance parameters. Combustion efficiency of the HTPB–boron–magnesium fuel is found to significantly increase for one of the fuels studied.

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1. Introduction

The use of boron as a fuel has great potential to increase the energy density of solid fuels used in ramjet applications.

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Boron has a high heat of combustion per unit volume, nearly three times larger than common hydrocarbon fuels [1]. Compared to aluminum, the current standard for high performance propulsion, boron has a volumetric heating value that is approximately 61% higher and a gravimetric heating value that is approximately 86% higher [2] assuming complete combustion.

There are well-documented challenges to the use of boron in solid fuels, however. Gany and Netzer [1] point out that boron tends to agglomerate before being discharged into the gas flow. Larger agglomerates require longer residence times to fully react within the ramjet combustor before exiting the nozzle. It has been demonstrated that boron requires high temperatures to ignite, around 1900 K for oxidizing environments at atmospheric pressure [3]. Natan and Gany [4] found that for a given boron particle diameter, only a specific range of ejection velocities would allow for sufficient particle heat induction times and promote full combustion within a ramjet combustor.

Another disadvantage of boron-containing fuels is that an oxide layer forms on the surface of the boron particles, creating a barrier between the unreacted boron and oxygen. The boron-oxide layer has a low melting point of just 723 K [2]. Consequently, the melted exterior of the particles on the fuel surface increases the adhesion and accumulation of the particles, further hindering dispersion. Large boron agglomerates therefore require long residence times, making it increasingly difficult to completely burn the boron before it exits the combustion chamber [5]. The presence of an oxide layer results in a two-stage combustion process for boron particles where the reaction with oxidizing species is diffusion limited until the oxide layer is stripped away, exposing the kinetically limited boron [6].

In experiments, the first stage of boron particle combustion is observed as bright particle glowing while the oxide layer is consumed [5]. The second stage is accompanied by the presence of a flame while the exposed boron is oxidized by surrounding gases. The first phase describes the induction time required to obtain particle ignition, which correlates with the removal of the oxide layer. In general, induction times for boron particles are reported to be long compared with aluminum [3,7].

There have been two main approaches to enhance the combustion of boron particles contained within solid fuel. The first method is to take a system-level approach to enhance the combustion of boron particles. Enhanced mixing of the oxidizer stream (e.g. use of a turbulator [8]), addition of an aft-burning section [9], or using a bypass air injection scheme (e.g. the PTV-N-4e test vehicles, Experiment Inc. [8]) are all methods to negate the inherent disadvantage of slow-reacting boron particles. However, each of these methods introduces irreversibility into the flow in the form of pressure losses, increases complexity, and adds inert weight to the propulsion system.

The second approach is to vary the fuel composition to incorporate ingredients that enhance boron combustion. It has been shown by Young et al. [10] that the addition of fluorocarbons, specifically polytetrafluoroethylene (PTFE), facilitates ignition of boron particles. It was found that some decomposition gases of PTFE react directly with boron oxide, therefore removing the oxide layer from the boron particles. Rapid removal of the oxide layer decreases the time required to reach the second phase of boron combustion described earlier. Various approaches for enhancing the combustion of boron including the use of nano-boron [11,12], fluorine containing compounds [13], and mechanical activation with other metals [14,15] have been reported. Many such studies are summarized in Ref. [16]. These studies typically present combustion measurements for boron used in high pressure propulsion or reaction applications.

Magnesium, which has an exceptionally low melting temperature of 923 K, has also been shown to improve boron combustion. Zolotko et al. [17] performed a study to test the effect of increasing magnesium concentrations on a two-component gas suspension with boron. It was concluded that across the tested range (0 wt% Mg to 20 wt% Mg), both ignition temperatures and ignition delay times were reduced as magnesium concentrations increased. Although completed in a gas suspension, this result is encouraging as a solution to promote boron combustion in a SFRJ. It was also found that the addition of both magnesium or PTFE to a hydroxyl terminated polybutadiene (HTPB) based fuel with boron enabled solid fuels to operate at a wider range of oxidizing environments in small-scale experiments [18].

While Mg appears to offer potential advantages to boron containing solid fuels, the energy density of the fuel is lower with its use. Any advantage gained by the use of Mg must overcome the loss in fuel energy density. The goal of the current study is to examine the effect of increasing amounts of magnesium on the ignition, surface composition, and combustion of boron-containing fuel. Holography and high speed image recording are conducted on the laser-assisted deflagration of solid fuels to examine the flame structure and particles ejected. Fuel performance parameters are measured and ignition experiments are performed on a test stand that replicates a realistic ramjet environment. Results are presented to demonstrate the advantages of Mg addition to solid fuels for ramjet application.

2. Experimental methods

2.1. Sample preparation

Four HTPB based fuels were prepared with varying amounts of boron and magnesium (reference Table 1). Each fuel consisted of HTPB R-45M (Cray Valley) as prepolymer, PAPI-94 (Dow Chemical) as the curative, amorphous boron (Atlantic Equipment Engineers, nominally 1 μm), and magnesium (Sky Lighter, +200-325 mesh). All fuels were prepared as follows: First, the HTPB liquid polymer was degassed for 15 min. Then the metals were hand mixed for 5–10 min in with the HTPB followed by the curative. The mixture was degassed again to minimize the

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