Combustion and Flame 191 (2018) 287–297

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Regression rates and burning characteristics of boron-loaded paraffin-wax solid fuels in ducted rocket applications

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ARTICLE INFO

Article history:
Received 21 September 2017
Revised 13 November 2017
Accepted 9 January 2018

Keywords:
Opposed flow burner
Boron nanoparticles
Combustion
Regression rate
SFDR

ABSTRACT

Boron based solid fuels have remained attractive for solid fuel ducted rocket (SFDR) applications since long due to their potential to release high energy on combustion. However, boron's energetic potential has not been successfully harnessed even till date in any practical combustion system. In view of this, present investigation is focused on utilizing boron nanoparticles embedded in paraffin-wax in various proportions (5–20% by weight) as solid fuel. To evaluate its performance an opposed flow burner (OFB) is used in presence of gaseous oxygen (GOX) and the oxidizer mass flux (G_{ox}) varies from 5 to 30 kg/m^2 s to estimate its regression rates relative to paraffin-wax. Burning process of boron loaded samples was captured using a high-speed camera to understand the ejection trajectory of the particles/agglomerates. Further, different material characterization techniques were employed on the pre- and post-burnt samples to understand the chemical and morphological changes and interlink that with overall burning characteristics. The active boron content determined from thermogravimetric analysis of pre-burnt sample, ejected agglomerates and post-burnt residue were 78.8, 34 and 18.7% respectively which confirm the combustion of boron nanoparticles up to a significant extent in the present OFB configuration. The present study may be helpful in futuristic application of hybrid propellant-based gas generator for SFDR systems.

1. Introduction

Ramjet is considered as the most reliable and simple among the available air-breathing engines and capable of providing very high specific impulse [1]. Since it has no moving parts, it is more suitable for operation at high speed and high temperature [2]. The origin of the ramjet is credited to China Lake (California, USA), who submitted a patent for ramjet as a propulsive device in 1909 [3,4]. Since ramjet is applicable for those systems which need propulsive device of higher range and endurance; therefore, it is most appropriate for military applications (medium and high supersonic speed range missiles) [1]. Some very well-known ramjet-based missiles across the world are Talos (USA), Sea Dart (UK), SA-6 Gainful (Russia), Kh-31 (Russia), and Brahmos (India) [5]. In present times, various types of ramjet engines are under investigation: these are liquid fuel ramjet (LFRJ), solid fuel ramjet (SFRJ), solid fuel ducted rocket (SFDR), etc. [4]. When the propellant booster (gas generator) is configured with ramjet and made a single unit, it is called integral ram rocket or ducted rocket which has higher specific impulse than a typical solid rocket [6]. In this way, SFDR contains two combustion zones (primary and secondary) due to which the design becomes challenging. It requires optimum transition from booster to sustained flight by ramjet operation and needs high energy fuel which can be ignited effortlessly to ensure effective transition [7]. In the secondary combustor of SFDR, fuel-rich hot gases further combust with the help of bypass air which is more stable than that of other types of ramjet engines having solid or liquid fuels; therefore, SFDR shows higher combustion efficiency and specific thrust [7,8].

Various researches have been conducted on SFDR where high energy metals/metalloids have been considered as additives to the solid propellant of the gas generator. Recently, boron has received renewed interest due to its outstanding heating value on both gravimetric and volumetric basis. It has the second highest heating value among the solid additives reported so far and could be well adopted as an energetic material in the formulation of propellants and explosives. Figure 1 represents a comparison of gravimetric and volumetric heating values of different fuel additives. In spite of high energetic potential of boron, unfortunately, it has not met the expected performance mainly due to the presence of native oxide layer on particle surface which inhibits its ignition/combustion process [9]. A pioneering study was conducted by Macek and Semple [10] where they had investigated ignition and combustion of a

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https://doi.org/10.1016/j.combustflame.2018.01.018

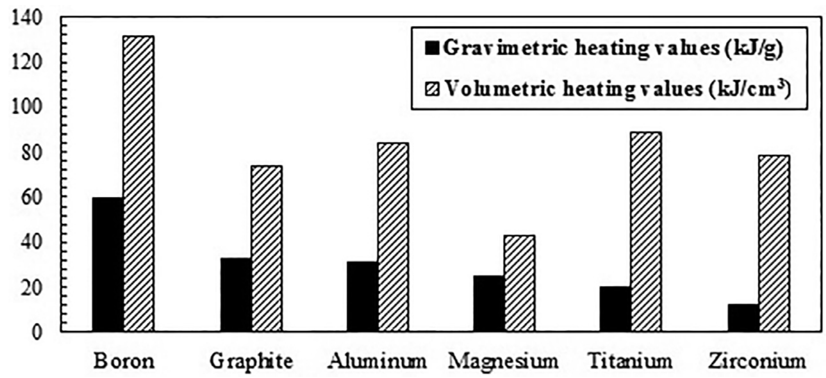

Fig. 1. Heating values of various fuels [26].

single crystalline boron particle at atmospheric pressure and identified the two-stage combustion process. The first stage comprises ignition of boron particle coated with a native oxide layer. The second stage comprises the combustion of bare boron on heating it above the boiling temperature of B_2O_3 and the oxide layer is completely stripped off by evaporation. Therefore, it is anticipated that removal of liquid oxide layer from boron particle surface plays a crucial role in the ignition and combustion process. Very limited studies have been carried out on boron as an additive in hybrid rocket/ducted rocket applications due to its problem during ignition and combustion. A detailed review on ignition and combustion of boron particle is available in the review article by Yeh and Kuo [11].

In a boron-based solid fuel the major combustion product is B_2O_3 which releases about 360 kJ/mole of latent heat of vaporization on its condensation [12]. Keeping that in mind, various researches have been conducted on boron-based fuel in a two-stage combustion chamber to utilize boron's full energetic potential [13–20]. Balas and Natan [13] examined the condensation of boron oxide using three different models to assess the performance of boron-based gel fuel through a two-stage ramjet engine where a part of inlet air is injected perpendicularly into the secondary chamber. In their study, first stage fuel-rich combustible products mixed with by-pass air of the secondary combustor and condensed before leaving the main nozzle. Boron particles coated with LiF/Viton A have also been investigated for fuel rich propellant by a ducted rocket, where it is found that the shortest ignition time is achieved for boron coated with LiF [21]. The behavior of individual boron particle has been investigated numerically where it is found that particle size and ejection velocity have a dominating effect on efficient ignition and combustion behavior of boron particles in the gas flow field of a solid fuel ramjet [22,23]. Some researchers developed windowed ramjet for visualization of combustion phenomena of boron loaded solid fuels to understand the regression rate and performance characteristics of such type of fuels [24,25].

Hybrid propellant based gas generator has also been studied by few researchers [8,27]. Recently, Komornik and Gany [8] used paraffin-wax with three different oxidizers as hybrid propellants for the gas generator of a ducted rocket and compared the performance with pure ramjet. On ignition and combustion, a fuel-rich gas generated by the gas generator is further reacted with bypass air stream in the secondary combustor. Hybrid gas generator is technically simple and it provides good control over pressure and mass flow rate of the burned gas. Gas generator having paraffin-wax as a fuel provides higher regression rate [8]. Similar observation has been made in hybrid rockets where the regression rate of paraffin-wax is 3–4 times higher than that of HTPB [28,29]. Additionally, hybrid fuels consisting of energetic nano-sized particles as additives often exhibit higher regression rate over base line fuels [30,32]. Therefore, paraffin-wax enriched with energetic additives can be potential fuel for hybrid propellant based gas generator in SFDR.

In the present study, an opposed flow burner (OFB) has been used to assess the performance in terms of regression rate and to understand the burning characteristics of boron particles in a solid fuel formulation. Pure paraffin–wax is considered as baseline fuel and a performance comparison is drawn between pure paraffin-wax and paraffin-wax containing boron nanoparticles. The concept of opposed flow burner has been available in literature since 1950s [35–40]. The opposed flow burner differs from cross flow configurations on flame structure, pressure levels, and oxidizer mass fluxes. However, this simple OFB system is often considered to be a useful tool for screening as well as characterization of hybrid fuels [41]. This screening study may also be helpful in design and development phase of SFDR. The existing solid fuel grain seems to have relatively low mass burning rate and it requires relatively large fuel surface area to obtain a particular thrust level. Energetic metal particles have been shown to improve the lower burning rate of solid fuels. The primary objective of the present investigation is to analyze the regression rates and burning characteristics of boron loaded paraffin-wax solid fuels (with varying particle loading) in presence of gaseous oxygen (GOX) as an oxidizer in an OFB system.

2. Experimental method

2.1. Composition of solid fuels and preparation of pellet

Paraffin wax and boron nanoparticles were purchased from Sigma Aldrich (Cat. No. 76242) and Nanoshel (Cat. No. NS6130-01-110) respectively. In our following study, 5, 10, 15 and 20 wt.% of this commercial boron nanoparticles (Nanoshel) were mixed with paraffin-wax (Sigma Aldrich) and referred as 595BW, 1090BW, 1585BW, 2080BW respectively.

Morphology of boron nano-particles before and after mixing with paraffin-wax was studied by scanning electron microscope (SEM: Model ZEISS EVO60) and transmission electron microscope (TEM: model JEOL JEM-2100 LAB6). A Japanese (JSM-7610F) field emission scanning electron microscope (FE-SEM) was used to study the morphology of burned out samples. For this purpose, burned particles were sputtered with gold and platinum plasma before placing into the FEM and FE-SEM respectively in order to minimize the charging effect. X-ray diffraction (XRD) analysis were performed on a Pan analytic system (X'Pert³ Powder) using Cu Kα ($\lambda = 1.5418$ Å) radiation to check the material crystallinity. The as-received particles and burned out combustible products were analyzed at 2θ values from 10°60°, with a step size of 0.05° and a rate