



Ignition and combustion characteristics of amorphous boron and coated boron particles in oxygen jet



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ABSTRACT

Boron (B) has an extensive application prospect in the field of aerospace propulsion. A jet flow pressurized concentrated ignition experimental system was designed to evaluate the ignition and combustion characteristics of both coated and uncoated floating B particles under different oxygen pressures. Ammonium perchlorate (AP) and nitroguanidine (NQ) were chosen as the coating agents, while the oxygen pressures ranged from 2 to 10 atm. The results of microstructure analysis show that after coating, grains of the coating agent attached to the surface of B particles and enhanced the specific surface area. During the ignition experiments, the sample particles experienced two stages (ignition stage and combustion stage) successively, depending on the presence or absence of B_2O_3 oxidation film. Both surface coating and increase in oxygen pressure can improve the ignition and combustion characteristics of the samples. Specifically, they can increase the combustion intensity, decrease the average ignition and combustion times (by up to 50%), and reduce their variations. Comparatively speaking, NQ coating showed more beneficial effects than AP coating. Therefore, the largest combustion intensity and shortest average ignition time and combustion time (4–5 and 5–6 ms, respectively) were achieved by the NQ coated sample at 10 atm oxygen pressure. Characteristic peaks of BO_2 , BO and Na (an impurity) were found in the maximum emission spectra of the samples. Increase in oxygen pressure was also found to be beneficial for improving the ignition and combustion characteristics of B particles coated with NQ.

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1. Introduction

Boron (B) is an important metalloid, and also a promising substitute for metal fuels. Among the common solid and liquid fuels for the aerospace industry, B has the highest volumetric calorific value (137.7 kJ/cm^3) [1]. However, it is not easy to release the high density energy in B particles. Due to its large oxygen demand and high melting and boiling points (2075 and 4000 °C, respectively [2]), B undergoes ignition and combustion with difficulty, and burns heterogeneously [3]. In addition, the oxidation product of B (B_2O_3) has a low melting point (450 °C) and a high boiling point (1860 °C). So, the B particles are wrapped in the liquid oxidation film during combustion, which hinders the permeation of ambient oxygen and affects the combustion efficiency [4]. Therefore, studies on ignition and combustion characteristics and modification methods of B are significant for its engineering applications.

Surface coating is a common modification method for metal fuels. Depending on the specific coating materials, coating may en-

hance the specific surface area of metal particles, improve the surface reactivity, or improve the compatibility between the particles and binders [5–10]. In the present study, two energetic materials, namely ammonium perchlorate (AP) and nitroguanidine (NQ) were chosen as the coating agents. AP is a widely known oxidizer for solid propellants, and a common coating agent for B as well [11]. NQ has a molecular formula of $CH_4N_4O_2$, and is an insensitive explosive. It is known for its good stability, superior performance, and slight erosion [12,13]. The main purpose for selecting these two materials is to improve the surface reactivity of B. Comparatively speaking, as an oxidizer, AP has higher oxygen content, thus it can offer more O_2 for B ignition [14]. On the other hand, as an explosive, NQ has higher combustion heat, thus it can raise the combustion temperature quickly. Moreover, some of the decomposition products (H_2O , NH_3 etc.) of these two coating agents can react with B or its intermediate products, which may promote the combustion [15,16].

In addition to the characteristics of B, external environmental factors such as pressure can also have a significant effect on the combustion of B [17]. Foelsche et al. [18] studied the ignition and combustion characteristics of B at 30–150 atm. The results showed that as the pressure increased, both the ignition delay and

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combustion time reduced. Ao et al. [19] studied the combustion time of two different stages during B combustion. The first stage involves the removal of the oxidation film, and the second stage is the combustion process of bare elemental B (sometimes the first stage is named as the ignition stage, and the second stage as the combustion stage [20]). They found that pressure had a more significant impact on combustion time than on ignition time. Furthermore, most existing kinetic models of B combustion consider pressure as one of the main influencing factors for B combustion time calculation [20]. Therefore, the effect of pressure on the ignition and combustion characteristics of coated B was analyzed in this work.

Compared to the static experiments, ignition of floating B particles is more difficult, but has more research value as well [21]. At present, a common method is to channel a B particle-carrier gas flow through a premixed flame. Chintersingh et al. [3,21] used N_2 as the carrier gas, and channeled B particles into an air/acetylene flame from the bottom. They measured the ignition delay and combustion time using a photomultiplier tube (PMT). Similar studies were conducted by Weismiller et al. [1] and Veith et al. [22], with various carrier gases, premixed flames, and measurement techniques. Young et al. [23] chose to channel the carrier gas from the side, so as to keep a certain distance from the burning surface of the premixed flame. The above method can no doubt ignite the floating B particles successfully, but there are some obvious drawbacks as well. Firstly, the carrier gas flow will interfere with the premixed flame structure and decrease the stability. Thus, the repeatability of the experimental results may be poor. Secondly, the overlap of premixed flame and B flame will make it difficult to characterize the combustion. Thirdly, the combustion environment is open, so the ignition does not occur under pressure, making it difficult to study the effect of pressure on ignition characteristics.

To overcome the above mentioned issues, an ignition method without open fire was used in this study. Yoshida et al. [24,25] reported that they ignited B lump with a xenon lamp. We adopted this method for the ignition of floating B particles after certain improvements. The carrier gas flow was channeled through the heating zone of the xenon lamp. The sample particles were then ignited under real-time monitoring with a high speed camera and a fiber optic spectrometer. The effects of coating materials and oxygen pressures on the ignition and combustion characteristics of B were comparatively studied. In addition, the microstructure analysis of the samples before and after coating was carried out using a scanning electron microscope (SEM).

2. Experimental section

2.1. Materials

Amorphous B (purity 99%, size distribution shown in Fig. 1) was used in this study and purchased from Baoding Zhongpuruituo Technology Co., Ltd., China. The coating agents AP and NQ (analytical reagent grade) were both purchased from Aladdin Industrial Co., China. The mass ratio between the coating agent and B was 1:10, and the detailed coating process has been described in our previous report [4]. The samples coated with AP and NQ were named as BAP and BNQ, respectively.

It is noteworthy that the so-called single amorphous B particles are in fact agglomerates of very small particles (typically in the submicron size range) [26]. Therefore, an amorphous B particle has a large internal reaction surface, and heat losses are limited to the external surface. As a result, amorphous B has lower ignition temperature than crystalline B, and thus is considered a more feasible candidate for practical applications [27].

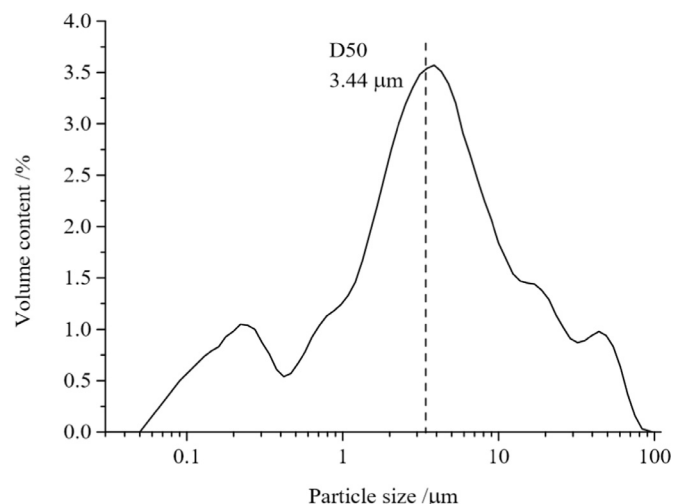


Fig. 1. Size distribution of B particles (D50 represents the median particle size).

2.2. Apparatus and methods

Figure 2 shows the setup of the experimental system designed for this study, which has been named as the jet flow pressurized concentrated ignition experimental system.

The schematic illustration of the entire system is presented in Fig. 2(a). The system consists of four parts, namely, the combustor module, the xenon lamp ignition module, the combustion diagnosis module, and the control module. The combustor module contains a pressure combustor and a sample injector, as shown in Fig. 2(b) and (c). The pressure combustor is surrounded by cooling water tubes, while in its center is a lug boss used for focusing. Light from the xenon lamp enters the combustor from the quartz glass window on the top. On one side of the pressure combustor is another quartz glass, which is used as the visual window. On the other side are three measuring holes, and the sample injector is fixed on one of them. The gas inlet and outlet are also on this side, by which the gas concentration and pressure within the combustor can be adjusted. The sample injector consists of a front platform, a gas channel, and an electromagnetic valve. Before experiments, the electromagnetic valve is fully closed, and the sample particles are placed on the front platform (see Fig. 2(c)). The carrier gas source is then connected to the tail of the injector, with a pressure higher than that in the combustor. Once the electromagnetic valve is opened, the carrier gas passes through the gas channel, and then blows and diffuses the sample particles into the combustor.

The heat source of the xenon lamp ignition module is a spherical short arc xenon lamp. In addition, an ellipsoidal cold light mirror is used for concentrating the xenon lamp light. On the two focal points of the ellipsoid are the centers of the xenon lamp and the pressure combustor, respectively. To prevent excessively high temperature, three electric fans are used for cooling the two heads of the xenon lamp.

The combustion diagnosis module includes a fiber optic spectrometer (AvaSpec-3648-USB2, AvaSpec, Netherlands), a color high speed camera (GE4900-T12, Redlake, USA), and an infrared thermal imager (T650SC, FLIR, USA). All the devices monitor the interior of combustor through the quartz glass visual window.

The control module contains a modulated power supply for the xenon lamp and a personal computer. The major function of the module is to control the on-off switching of all the electronic devices and save the data.

In the present work, the xenon lamp power was set to 7 kW. Before every test, the xenon lamp was turned on in advance, and the

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