



Combustion of boron particles in products of an air–acetylene flame



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ABSTRACT

Boron is an attractive fuel for propellants and explosives because of its high volumetric and gravimetric energy density. However, despite multiple previous studies, burn times and combustion temperatures of fine boron particles in well-characterized environments are not well known. The aim of this work was to characterize the combustion of boron particles injected into air–acetylene flames and to determine their burn times and combustion temperatures as a function of their size. The experiments used 95% pure commercial boron powder with particles in the range of 0.4–30 μm . Premixed acetylene–air flames with varying equivalence ratios (0.62 and 1.65) were produced. Boron powder was injected axially into the flame combustion products with a nitrogen jet. The particle size distributions were determined using powder that exited from the injector and captured directly on to microscope slides. Agglomerated particles fed into the flame were observed directly and accounted for in the particle size distributions. Powders were analyzed using scanning electron microscopy (SEM) and particle sizes were corrected accounting for the fractal dimensions of the observed agglomerates. The measured burn times were correlated with the obtained particle size distributions to recover the effect of particle size on its burn time. The environment in which the particles burned was characterized in detail using computational fluid dynamics. Results indicated that for micron-sized amorphous boron particles, their time, t_b , in ms, can be described as a function of the particle diameter, d , in μm , as $t_b \approx 4.73 \cdot d^{0.75}$. Average combustion temperatures exceed 2600 K in a pre-mixed hydrocarbon flame environment and show no significant correlation with particle size or burn times.

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1. Introduction

Metals are used in propellants and explosives due to their high oxidation enthalpies, high combustion temperatures, and low molecular weight products. Particularly, there has been interest in the use of boron due to its high volumetric and gravimetric heating values [1] compared to other metal fuels like magnesium and aluminum [2,3]. However, it is difficult to recover the full energy of boron oxidation in practical combustion applications. This has been attributed to its delayed ignition caused by its protective oxide coating [4–6] and long combustion times [7–14]. Research further suggests that during boron combustion, heterogeneous surface reactions occur at relatively low combustion temperatures [15] because of its high boiling point. Formation of relatively stable intermediates and less thermodynamically favorable products, such as HOBOR is widely considered as another limitation for boron combustion in hydrogen containing environments [13]. Polymorphic phase transitions [16], crystallinity, particle size and surface mor-

phology of boron particles have also been reported to affect both its ignition and combustion [17].

Despite an extensive and sustained effort to understand boron combustion, majority of the published work focused on quantifying its ignition delay and oxidation kinetics [1,5,10,18–21]. There are limited published data on the combustion times of fine boron particles and no record of the measured boron combustion temperatures.

From the data available, correlations between the size, d , and burn times, t , for coarse crystalline [7–9] and more recently nano-sized boron particles [13] have been presented in the form of common $t \sim d^n$ trends (power law, with the exponent, n). No similar correlations are available for the most common, and more affordable micron-sized amorphous boron powders. Published experimental results and respective power law trends proposed for fine boron particles are inconsistent between one another. For example, burn times for 7 and 10- μm , 99% pure boron particles were reported to be 1.5 and 2.2 ms, respectively, for the powders injected into combustion products of methane/oxygen/nitrogen flames [11]. These results are in agreement with an experimental trend and respective power law, with $n = 1.35$ implied by earlier studies with much coarser particles [7–9]. Even shorter burn times of

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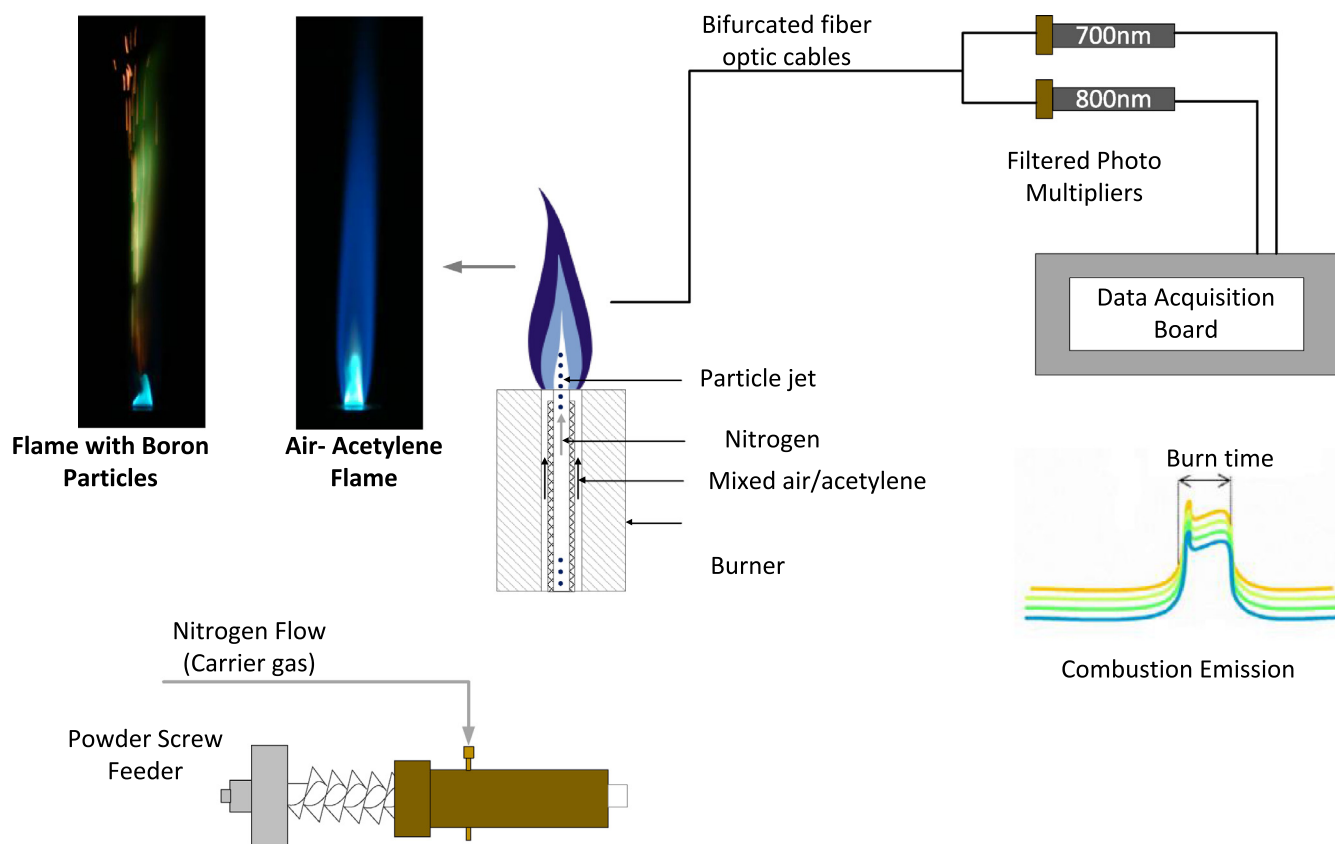


Fig. 1. Schematic diagram of the experimental setup and photographs of air-acetylene flame at equivalence ratio 1.65 with and without particle feed.

0.24–0.42 ms and 0.2–1 ms were recorded for 7.2 μm and 20 μm boron particles respectively, ignited by a reflected shock wave at elevated pressures [20,21]. Conversely, burn times for smaller, 2.5 and 3 μm particles (respectively 93% pure amorphous and 99.5% pure crystalline), injected into a hydrocarbon fuel flame were reported to be longer, 4.1 and 4.6 ms, respectively [10]. In both Refs. [10] and [11] flat flames using methane as a fuel were used. Thus, the discrepancy between the reported boron burn times is unlikely to be attributed to a difference in the composition or temperature of the oxidizing environment. Although boron powders with different purities and crystallinities were used in different studies, it was reported that the effect of boron crystal structure on its combustion is negligible [10]. Crystallinity was reported to affect ignition of boron, however [19]. More recent experiments with still finer 0.674 μm 99% pure amorphous boron particles [13] suggest burn times greater than 2 ms, also in disagreement with the trends implied by previous experiments [7–9,11]. One possible reason for such discrepancies maybe that in all previous studies, a specific size was assigned to a powder sample used in the experiments. However, all such powders contained particles of different sizes, and the measured burn times could have been biased to specific subsets of particles, depending on how the particles were injected in the flame and how the combustion time was measured in each case. Particles could also have been agglomerated, which would affect the measured burn times substantially. Another possible reason for the discrepancy in the measured particle burn times is that different indicators were used to identify combustion in different studies. In Ref. [10], the burn times were determined from the lengths of the photographed particle streaks. In Ref. [13], durations of pulses recorded by filtered photo-sensors were used. In Ref. [11] scattered light from a 489 nm line argon-ion laser was recorded at two angles by two photomultipliers (PMTs). The inten-

sity of the scattered light decreased as the particles burned out. The distance over which the intensity of the light scattering signal decayed and particle velocity were used to infer particle burn times.

Thus, careful measurements are still needed to address specifically the effect of boron particle size on its burn time and take into account possible agglomeration of boron particles. As noted above, measurements of temperatures of the burning boron particles are also currently lacking. The objective of the present study is to clarify the existing discrepancies and obtain the missing data characterizing combustion of fine boron particles in well-defined oxidizing gas environments.

2. Experiments

2.1. Experimental setup

Aerosolized particles were fed axially into a premixed annular air-acetylene flame. The experimental setup is shown schematically in Fig. 1. It has been described in detail elsewhere [22–24]. The mixed gases were fed through a 50-mm long, 19.13-mm diameter tube that was tapered to form a 5.16-mm nozzle of the burner. Flames with two equivalence ratios ($\phi = 1.65$ and 0.62) were created by varying the acetylene flow rate between 0.64 and 0.24 L/min and maintaining the air flow at 4.72 L/min. All flow rates were measured using individual rotameters. Acetylene was used to minimize soot production and readily achieve high flame temperatures in a broad range of the air/acetylene equivalence ratios. As for the other hydrocarbon fuel gases, combustion products mostly comprised CO_2 , CO and H_2O , which served as main oxidizers for boron particles, similarly to previous experiments [10,11,13].

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