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Combustion characteristics of well-dispersed boron submicroparticles and plasma effect

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ABSTRACT

Boron is an attractive high-energy fuel additive. But it could not burn efficiently in practical systems due to its high ignition temperature and slow burning velocity. Finding methods to enhance the combustion of boron is desired. This work focused on the combustion characteristics of boron submicroparticles with and without plasma discharges in a hot environment supported by $CH_4/N_2/O_2$ flat flame based on the optical diagnostics. The boron submicroparticles were dispersed by the nebulization method to control the agglomeration. The well-dispersed boron flame exhibited two different burning modes, depending on the ambient temperature. As the ambient temperature was above 1520 K, the boron flame showed definitely two-stage characteristics where the upstream of particle flow was yellow, corresponding to the first-stage flame, while the downstream was green and diffusive, corresponding to the second-stage flame. The first-stage and second-stage burn times were respectively in the range of 0.46–1.08 ms and 0.92–1.87 ms, as the ambient temperature decreased from 1752 K to 1520 K. The chemical kinetics-controlled mechanism was confirmed by the nearly linear size dependence of the burn time (d^1 law). Nevertheless, as the ambient temperature was below 1520 K, the boron submicroparticles were partially burned or oxidized, exhibiting a mildly orange stream. This mild boron flame could be enhanced using a plasma discharge. The ignition delay time was shortened from 3.06 ms to 0.77 ms when the discharge was introduced at the ignition delay stage. The two-stage combustion characteristics occurred when the discharge was introduced at the combustion stage.

1. Introduction

Boron is an attractive high-energy fuel additive, mainly for solid propellant in the past, since the volumetric energy density of boron is much higher than those of hydrocarbons, or most metals [1,2]. However, it is difficult to use boron effectively in practical combustion devices because of its poor combustion characteristics such as high ignition temperature and long burn time.

In order to solve these problems, lots of research on the combustion of boron particles has been carried out since 1960s. The igntion temperature of large boron microparticles was as high as 2000 K [3]. The boron flame exhibited two-stage combustion characteristics [3–5]. During the two-stage combustion, the first- (t_1) and the second-stage burn time (t_2) of boron microparticles with the diameter of 34.5 μm are respectively in the range of 2.6–5.0 ms and 7.0–17.3 ms, as the ambient temperature is in the range of 2240–2870 K [3]. The t_1 and t_2 of boron particles with the size of 2–3 μm are respectively in the range of 1.48–2.16 ms and 2.33–2.84 ms, as the ambient temperature is in the range of 1772–1993 K [4]. It is concluded that finer boron microparticles have better combustion characteristics, including the shorter burn time. However, as the size of boron particles decreases down to the nanoscale, the burn time does not keep shortening. The t_1 and t_2 of boron nanoparticles with the mean diameter of 60 nm are respectively in the range of 1.5–2.2 ms and 1.5–2.0 ms [5], which are close to those of the microparticles with the size of 2–3 μm at the similar ambient temperature of around 1810 K [4]. This lack of size dependence was not well understood yet [5]. Thus, more

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Nomenclature

a	Fitting coefficient
A	Pre-exponential factor
b	Fitting index coefficient
C_{pB}	Thermal capacity of solid boron
$C_{pB_2O_3}$	Thermal capacity of boron oxide
d	Diameter
$D_{B_2O_2,g}$	Diffusivity of $B_2O_{2(g)}$
E_a	Activation energy
h	Convective heat transfer coefficient
j	Current density
l	Height above the burner
l_1	Height 1 above the burner
l_2	Height 2 above the burner
M_B	Molecular weight of boron
$M_{B_2O_3}$	Molecular weight of boron oxide
Nu	Nusselt number
P	Power
P_0	Atmospheric pressure
$P^0_{H_2O}$	Equilibrium vapor pressure of $B_2O_{2(g)}$
P_{H_2O}	Partial pressure of $H_2O_{(g)}$ in the ambient gas
P_{O_2}	Partial pressure of $O_{2(g)}$ in the ambient gas
Q_1	Vaporation heat
Q_2	Heat of reaction with O_2
Q_3	Heat of reaction with O_2/H_2O
r_p	Radius of the boron particle
R_1	Rates of vaporation
R_2	Rates of reactions with O_2
R_3	Rates of reactions with O_2/H_2O
R_u	Gas constant
t_1	First-stage burn time
t_2	Second-stage burn time
t_d	Ignition delay time
T_0	Room temperature
$T_{critical}$	Critical temperature to ignite boron particles
$T_{initial}$	Initial temperature of boron particles
T_p	Particle temperature
T_∞	Ambient temperature
u_0	Velocity of boron particles as l is not larger than 5 mm above the burner
u_l	Velocity of boron particles as l is larger than 5 mm above the burner
x	Thickness of oxide layer
$X_{BO,\ s}$	Equilibrium mole fraction of $(BO)_n$ on the particle surface
X_{O_2}	Mole fraction of O_2 in the ambient gas

Greek symbols

ε_B	Measured emissivity of boron particles during first-stage combustion
α_1	Evaporation coefficient of the $(BO)_n$ polymer
α_2	Reaction probability of an O_2 striking a $(BO)_{n(l)}$ molecule
α_3	Reaction probability of an H_2O striking a $(BO)_{n(l)}$ molecule
ν_1	Hertz–Knudsen impingement factor of $B_2O_{2(g)}$
ν_2	Hertz–Knudsen impingement factor of $O_{2(g)}$
ν_3	Hertz–Knudsen impingement factor of $H_2O_{(g)}$
ρ_B	Density of boron particle
$\rho_{B_2O_3}$	Density of boron oxide
σ	Stefan–Boltzmann constant
τ_c	A factor, no specific meaning

Subscript

a	Adsorbed species at surface
g	Gas phase
l	Liquid phase

research on the combustion characteristics of finer boron particles is needed.

Besides the fundamental research on combustion characteristics of boron particles, many auxiliary methods have been explored to enhance the combustion of boron, such as reducing the particle size [6], coating various “aids” or “dopants” on the surface of boron particles [7], adding H_2O or fluorine in the ambient gas [8–10]. Thereinto, using the finer particles is favorable [11–15], because it avoids not only the toxicity of fluorine, and the low efficiency resulted from using H_2O, but also the complicated coating process engineering. On the other hand, plasma has been a promising technique to enhance the ignition and combustion of hydrocarbon fuels in the last two decades [16–18]. For the potential applications in internal combustion engines, gas turbines and scramjet engines, plasma-assisted ignition (PAI) and plasma-assisted combustion (PAC) have drawn considerable attentions. New PAI/PAC techniques have been developed [16–20]. Mechanisms of the interaction between plasma and hydrocarbon flames have been further understood [16–20]. Nevertheless, to the best of our knowledge, there is almost no publication about the PAI or PAC of boron particles. Therefore, it is of great interest to combine the plasma and the combustion of boron as well as study their interactions.

In this work, the combustion characteristics of boron submicroparticles are first diagnosed and quantified based on the digital color images of boron flame. Well-dispersed boron submicroparticles are generated by a particle feeding system to avoid agglomeration. The plasma discharge is coupled with the Hencken burner to assist the combustion of boron submicroparticles, verifying the plasma effect on the boron flame.

2. Experimental

2.1. Particle feeding and burning system

Figure 1 shows the schematic of the particle feeding and combustion system. A home-made multi-diffusion flat flame burner, Hencken burner, is employed to support a hot environment for the combustion of boron submicroparticles. The Hencken burner is mainly made up of a $53 \times 53 \times 12$ mm^3 honeycomb matrix, where 156 stainless steel capillary tubes (OD = 0.8 mm, ID = 0.7 mm) are evenly distributed. Those capillary tubes are sealed from the open cells of the honeycomb matrix. The gaseous fuel (CH_4) flows through the capillary tubes, while the oxidizing gas stream (N_2 and O_2) passes through the open cells of the honeycomb matrix surrounding the fuel tubes. This configuration produces a small, laminar diffusion flame at the exit of each fuel tube. Those laminar diffusion flames form a high-temperature post flame region isolated from the surrounding cold air. A stainless steel tube (OD = 3 mm, ID = 2 mm) is inserted into the center of the honeycomb to provide a passage for the boron submicroparticles to enter into the post-flame zone.

A particle feeding system, including ultrasonic dispersion, nebulizing and diffusion drying, is used to generate the well-dispersed submicroparticles [21]. Boron submicroparticles are ultrasonically