Combustion of pyrotechnic composites for micro tube

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Abstract

The combustion of pyrotechnic composites charged in micro-tube is important to applications in space engineering, such as micro propulsion. $B/BaCrO_4$ and B/KNO_3 are two typical composites in pyrotechnic devices. In the reaction of pyrotechnic composites, more condensed phase products will enhance resistance and friction to gaseous flow to induce combustion disturbance and burning rate growth. The combustions of $B/BaCrO_4$ show pulsed combustion induced by forming and separating of condensed product layer cyclically, and burning rate is linear growth depending on boron content increase. The combustions of B/KNO_3 show friction effect of micro tube and resistance effect of condensed phase product significantly below 0.5mm internal diameter. The growth of internal pressure induced by friction and resistance is an important factor let burning growth and disturbance, even deflagration. The burning rate growth of micro tube charge depends on environment pressure, but disobeys exponential increase as conventional propellant.

1. Introduction

Combustion characteristics and mechanism in micro size scale are very important to design micro engine or micro propulsion thruster. Davy H [1] studied combustion phenomena in narrow ditch early, and found flame can propagate along sub-micro scale ditch in some conditions, and micro scale effects are very strong on combustion [2]. After analyzed combustion of micro-gas turbine engines, Waitz I A [3] found the heat loss is higher two order of magnitude in micro scale than in convention scale. Liu [4] simulated premixed combustion in the 2mm internal diameter tube, the results shown released heat of micro burner is 10% of reaction heat, in which radiation heat is 80%-90% of total lost heat. Li [5] analyzed H_2/Air premixed combustion in micro tube in experiments and simulations, in that the results shown the loss of heat from tube wall accounts for 40% of total released heat, in which the radiant radiation heat loss is 4-5 times of convective heat loss. Micro scale effects, such as heat loss and flow friction, can reduce burner efficiency and induce combustion disturbance, even flameout. Jiang [6] researched methane diffusion flame and its flameout in micro scale, it was found that the rate of burning out the delay significantly enhances depending on downsizing burner scale. Pyrotechnic combustions are more complexity than the combustion of gaseous flues, which will produce solid products, and belong to gas-solid two-phase flow. Wu [7] found intermittent burning of $B/BaCrO_4$ in micro tube, in that solid products enhancing flow friction. Liu [8] simulate pyrotechnic composites burning in micro tube, the results shown the stability of burning depending on the loss of heat from tube wall, whose thickness of wall thickness is good for stability burning. Liu [9] also researched combustion stability of B/KNO_3 in micro tube, it was found that flow friction will enhance burning, even induces flash breakdown of charge and solid product layer. Pyrotechnic composites are easy to burning in low pressure environment, sometimes are used as propellant for micro propulsion thruster, but the combustions are complex. In the paper, we will show interesting combustion characteristics of pyrotechnical composite in micro scale.

2. Experiments

2.1 Preparation of Sample

$B/BaCrO_4$ and B/KNO_3 were selected as samples to study burning characteristics in micro tube。 The ingredients of Pyrotechnic composites are seen in Table1.

Table1: Mass ratios and Oxygen equilibrium coefficients of $B/BaCrO_4$ and B/KNO_3

Composition	Fuel	Oxidant	Binder (Phenolic resin)	OEC	Density (g/cm^3)
$B/BaCrO_4$	8	92	1%	-8.4	2.5
	12	88		-17.6	
	14	86		-22.2	
	16	84		-26.8	
B/KNO_3	40	60	10%	—	1.4

$B/BaCrO_4$ and B/KNO_3 composites are step by step pressed into different tubes. The PMMA tube (internal diameter: Φ3. 5, wall thickness: 2.4mm, length:42mm) and the quartz Micro tube (internal diameter: Φ0. 5, Φ1. 0, Φ1. 2, Φ1. 5, Φ2. 0, wall thickness: 1.0mm, length: 50mm) are for $B/BaCrO_4$ and B/KNO_3 respectively.

2.2 Experimental Apparatus

The burning rates of composite charge were tested by a high speed camera in a transparent combustion chamber under constant pressure and the sample was ignited by a Nd:YAG pulsed laser. The apparatus are shown in Figure 1.

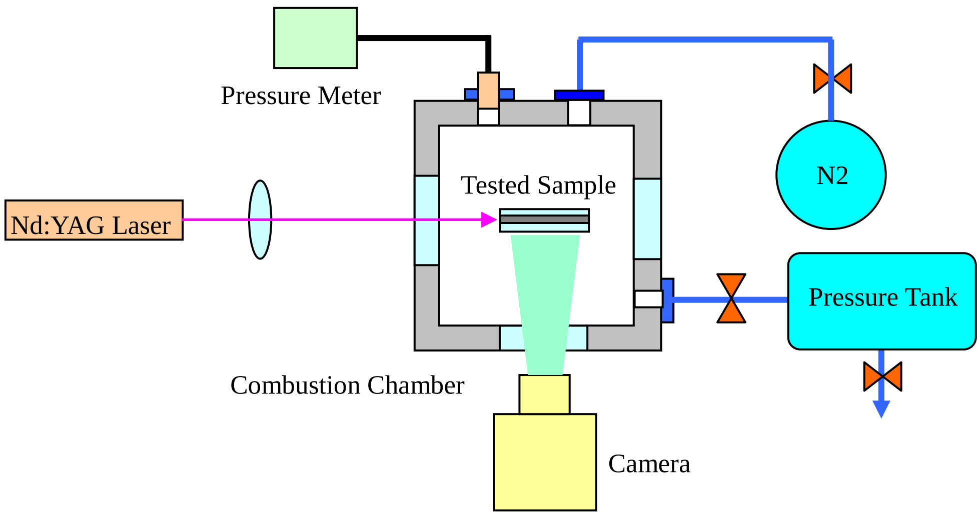


Figure1: Scheme of experiment instrument

3. Results and Discussion

3.1 B/BaCrO4 combustion in micro tube

The burning processes of $B/BaCrO_4$ micro tube were record by high speed camera in 0.1 MPa N_2 environment, shown in Figure 2.

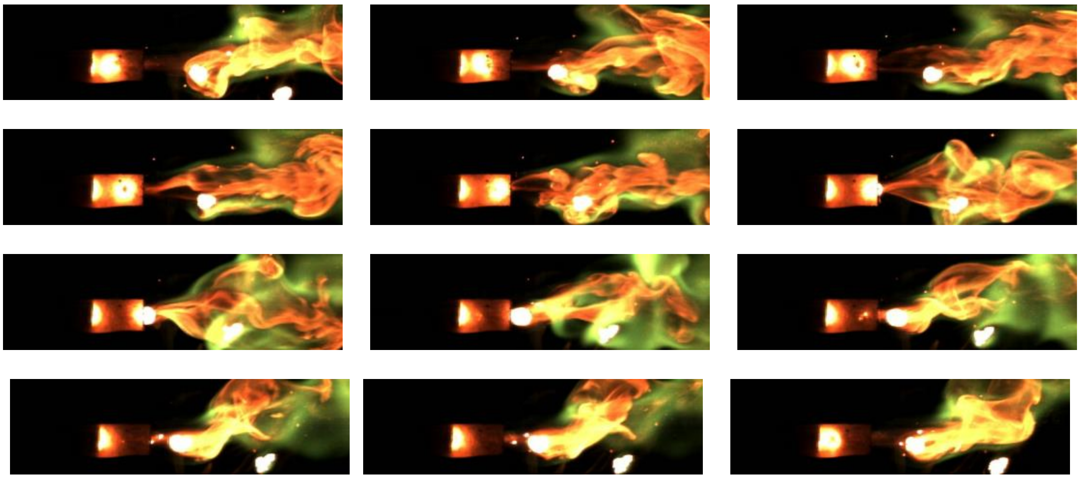
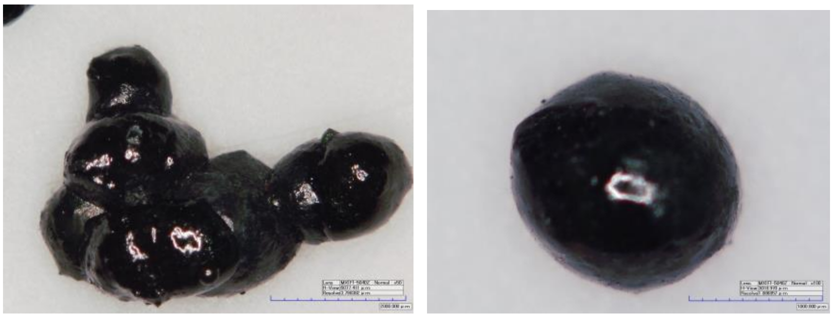


Figure2: B/$BaCrO_4$(14:86)burning processes, at 2ms interval time

In the burning process of B/$BaCrO_4$ composites at selected mass ratios, the pulsed condensed product will be formed. The collected solid products are analyzed by microscope, shown in Figure3 and Figure4. The length of condensed product layer is ~1.2mm, separation cycles is ~17.8ms.

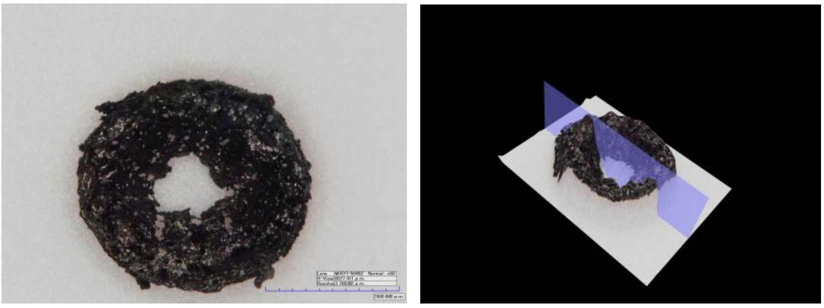


(a) multi-melted drops (b) single melted drop

Figure3: Shapes of Combustion products of B/$BaCrO_4$ (8/94) at state of cooling

（a）cake shape

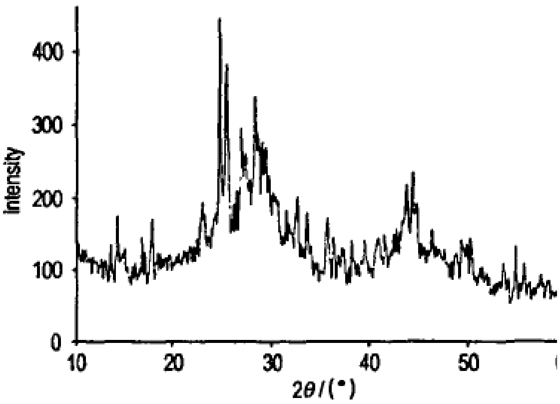
（b） depressed cake shape



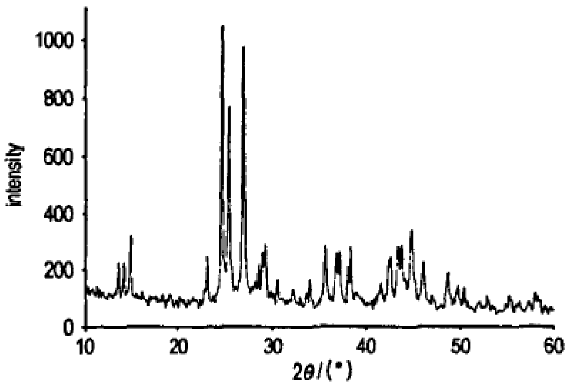
（c） doughnut shape

Figure4: Shapes of Combustion products of B/$BaCrO_4$ (a:12/88, b:14/86, c:16/84) at state of cooling

The solid products of B/$BaCrO_4$ (8/92, 14/86) were analyzed by XRD, seen Figure5. Analyzed results shown the major constituents of solid products are BaB_2O_4, B_2O_3, BaO, Cr_2O_3 and CrB2, seen Table2.



(a) Boron content is 8%



(b) Boron content is 14%

Figure5: XRD spectra of combustion condensed products

Table2: Composition of Products corresponding spectral peaks of XRD

product ingredient	2θ/(°)	
	B/$BaCrO_4$(8/92)	B/$BaCrO_4$(14/86)
BaB_2O_4	14.16,24.62,25.34,43.82,54.88	14.12,24.60,25.32,43.30
B_2O_3	14.16,22.92,28.24,43.82	14.12,23.04,28.52,30.56,43.30,48.70
BaO	—	13.54,33.94,42.56,46.14
Cr_2O_3	24.62	23.04,33.94,36.82
CrB_2	—	29.18,46.14

Obeying fundament of inorganic chemistry, the reaction products of Boron and BaCrO4 have following possible reaction.

$$2B(s)+2BaCrO_4(s)\rightarrow Ba_2O_3(s)+2BaO(s)+Cr_2O_3(s) \quad (1)$$

$$4BaCrO_4(s)\rightarrow 4BaO\,(s)+2Cr_2O_3(s)+3O_2(g) \quad (2)$$

$$4B(s)+3O_2(g)\rightarrow 2B_2O_3(s) \quad (3)$$

In according to pictures of burning processes, we found chemical reactions are solid-gas reaction, and some condensed products vaporize to gas phase products, the possible products are with low boiling point, seen Table 3.

Table3: Thermo-physical parameters of possible combustion products of B/$BaCrO_4$

substance	melting point（℃）	boiling point（℃）	reference
glass B_2O_3	294	2100	Ref[10]
Crystal B_2O_3	450	1500	Ref[10]
BaO	1918	2000	Ref[10]
Cr_2O_3	2266	4000	Ref[10]
CrB_2	842	—	Ref[10]
α-BaB_2O_4	1095	—	Ref[10]

When the pressure difference is lager than tensile strength, layer will be drove by difference. The pressure difference between two sides of layer is decided by the inner tube pressure and surface pressure at burning surface, the length of layer and separation cycle can be calculated theoretically.

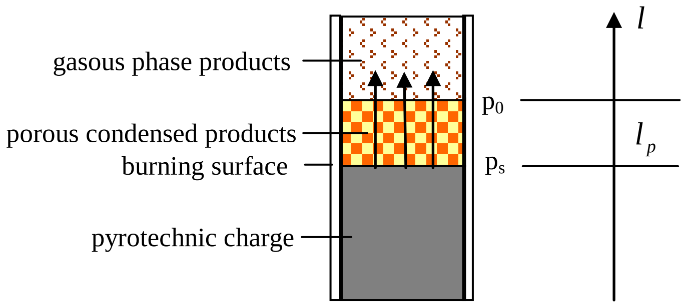


Figure6: Modeling of flame structure for pyrotechnic combustion of micro tube

If $p_s - p_0 \geq \sigma_s$, the length of condensed products and separation cycle are,

$$l_p = \sigma_s / k \quad (4)$$

$$\tau_{cycle} = \int_0^{l_s} \frac{1}{ap^n} dl \quad (5)$$

Where, k is resistance coefficient, l_p is length of separated condensed product layer, σ_s is tensile strength of condensed product layer, a and n are burning rate coefficient and pressure rate coefficient and pressure exponent respectively.

Analyzing the pictures of combustion process, the burning rates of B/$BaCrO_4$ were shown in Figure7. The burning rate depends on linear growth of boron content, seen Figure7.

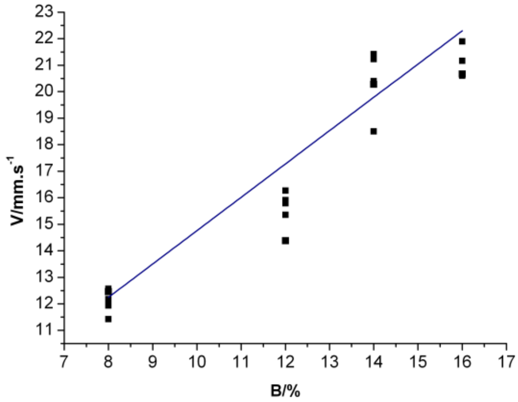


Figure7: Burning rate of B/$BaCrO_4$ at 0.1MPa

3.2 B/KNO_3 combustion in micro tube

B/KNO_3 combustion processes in Φ1.0mm micro tube were shown in Figure8 at 0.1MPa, in which the first two images shown laser ignition of charge.

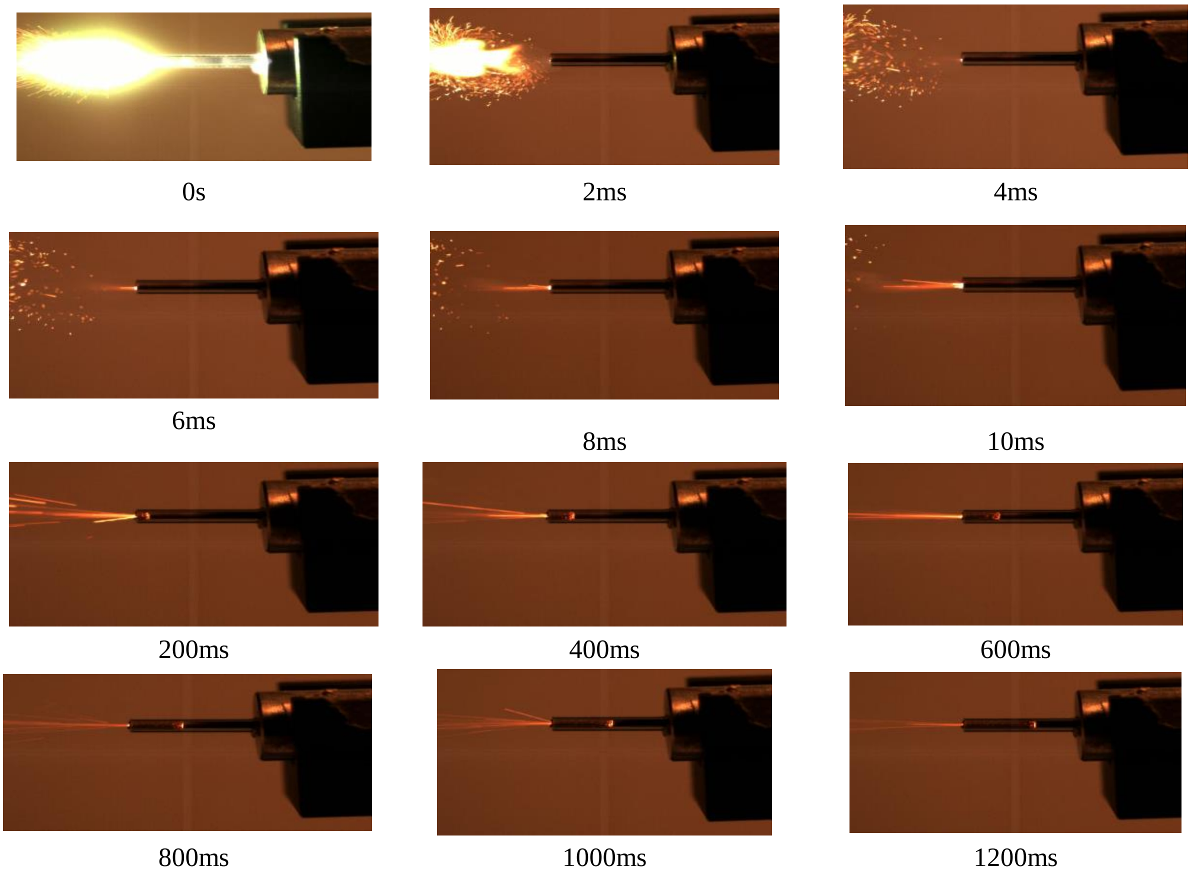


Figure8: B/BKNO_3 combustion processes in Φ1.0mm internal diameter micro tube at 0.1MPa N_2 environment

The friction of micro tube and the resistance of condensed phase products to gaseous phase products can not be ignored for micro tube combustion. Figure9 shown the resistance effects of resistance, that is the burning rate will increase depending on the burned displacement in micro tube, such as at Φ1.0mm internal diameter. An interesting flash breakdown phenomenon can be found in small internal diameter tube, because of resistance of condensed phase products inducing deflagration.

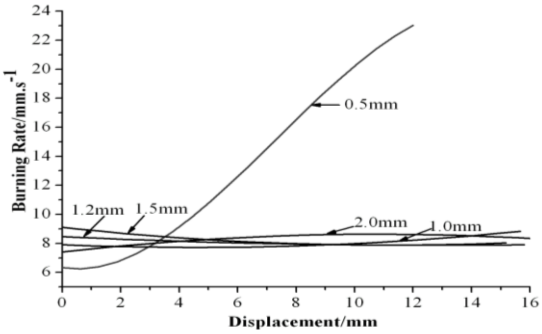


Figure9: Burning rates depending on the burning displacement at different internal diameters and 0.1MPa

Environment pressure is another important effect on burning rate, seen Figure10. The burning rates depend on the environment pressure to rise. The choking phenomenon of gas-solid flow can not found at over 0.1MPa environment pressure, but the resistance of condensed products and micro tube still exist to enlarge burning rate.

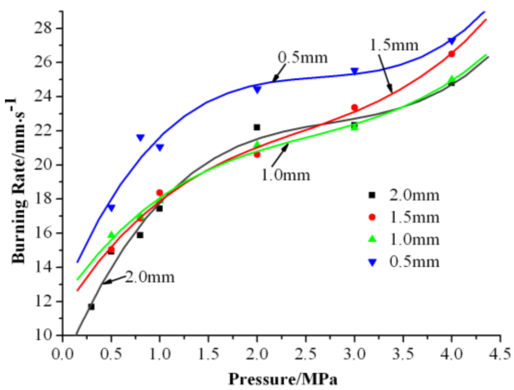
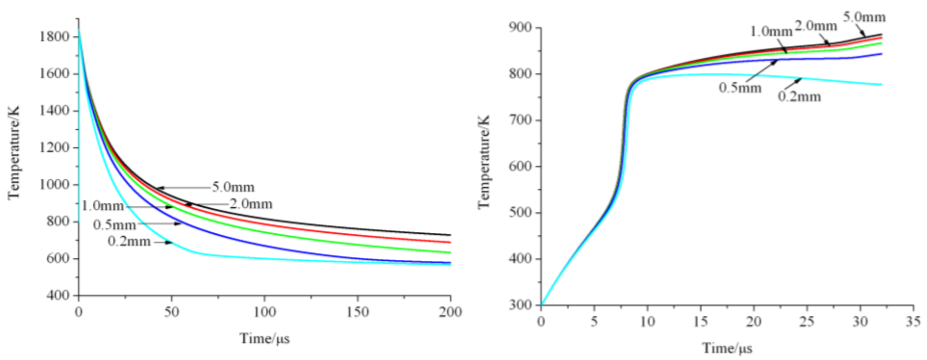


Figure:10 Dependence of burning rate on environment pressure.

Liu[8] Simulated results also shown micro scale effects on temperature distribution., seen Figure11. Temperature decaying in flame zone and temperature rise in preheat zone depend on the internal diameter of micro tube. The temperature of flame zone decays fast at small diameter tube, and similarly the temperature of preheat zone rises to lower level, because of heat loss. It also found that the temperatures at 1.0mm, 1.5mm and 2.0mm diameter of micro tube are close to each other, but not at below 0.5mm diameter. The burning temperature distributions can shown the similar tendency of burning rate at different pressures.



(a) temperature in flame zone (b) temperature in preheat zone

Figure11: Temperature in preheat zone and flame zone at different diameter quartz tube

4. Conclusions

The combustions of pyrotechnic composites in micro tube are more complex than gaseous phase combustion, since more solid products can be produced to enhance resistance to gaseous flow, and micro tube friction and heat loss also can effect on their combustion. The recorded images shown B/$BaCrO_4$ reaction is solid-gas reaction, but in the early, the reaction was considered as pure solid reaction or less gaseous reaction. The difference pressure between condensed phase product layer will drive the layer separating from burning surface to induce pulsed combustion. And another result is that the dependence of burning rate of B/$BaCrO_4$ on the linear growth of boron content. The more gaseous products will be formed in B/KNO_3 combustion than in B/$BaCrO_4$. The resistance of condensed products and the friction of micro-tube wall will enhance significantly. When the internal diameter of micro tube is small below to a critical size, resistance and friction effects will let the pressure growth to induce combustion disturbance and burning rate growth. The environment pressure is another effect on combustion. The burning rate depends on the pressure in linear growth, but the growth trends disobey exponential increase tendency.

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