Research on the combustion mechanism of boron-based fuel-rich propellant under low pressure

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Abstract

Temperature distribution of combustion wave and the quench combustion experiments were carried out for two boron-based fuel-rich propellants under low pressure, and the quenched surfaces of the propellants were analyzed with SEM and EDS. The results showed that coating boron with AP could increase the combustion temperature, pressure exponent and combustion intensity, while made the combustion process become more complicated. A “deposit” layer was found to be formed when the boron-based fuel-rich propellant burned under low pressure, and the combustion process of the propellant could be divided into two reaction zones, one of which was condensed reaction zone on and near the combustion surface, and the other was gaseous reaction zone in the pores of the inert “deposit”. Considering the formation of “deposit”, a combustion model was established based on BDP combustion model, and the combustion characteristics of boron-based fuel-rich propellant under low pressure could be interpreted well by the model.

Keywords : boron-based fuel-rich propellant, combustion mechanism, deposit, combustion model

1. Introduction

Boron-based fuel-rich propellant is a kind of solid propellant with the highest energy in present, and it is mainly applied in the solid fuel ramjet (SFRJ) to increase the specific impulse of the common solid rocket motor1)−3). Among SFRJ, unchoked SFRJ is an attractive propulsion system for the intermediate and long-range air to air missile because of the high specific impulse and the simple structure. However, the flight condition (height and Mach number) of the motor changes constantly and results in the continuous change of the chamber pressure, which requires the fuel-rich propellant combusts steadily in a large range of pressure.

In boron-based fuel-rich propellant, ammonium perchlorate (AP) is widely used as oxidizer, but the composite propellant with AP usually combusts under the pressure higher than 2MPa because AP cannot combust steadily when the pressure is lower than 20 atm4). However, in unchoked solid fuel ramjet, the chamber pressure may be as low as 0.2 MPa in the gas generator, and the boron-based fuel-rich propellant should be able to combust steadily under low pressure of 0.2~1 MPa so as to provide stable impulse for the ramjet.

The pressure exponent of the propellant denotes the relationship between the burning rate and the pressure, and it is mainly affected by the gas phase combustion. In general, under low pressure, condensed phase combustion is enhanced while gas phase combustion is weakened, which leads to the lower pressure exponent. But the pressure exponent of boron-based fuel-rich propellant under low pressure is usually much higher than that under high pressure, and this indicates that the combustion mechanism of boron-based fuel-rich propellant under low pressure is different from that of the common composite propellant.

In order to study the combustion mechanism and improve the combustion performance of the boron-based fuel-rich propellant under low pressure, temperature distribution of combustion wave was measured by the fine thermo couple and the quench combustion experiments were carried out for two boron-based fuel-rich propellants under low pressure. Then, the morphology and elemental composition of the quenched surfaces were analyzed with SEM and EDS. Moreover, a new combustion model for the combustion of boron-based fuel-rich propellant under low pressure was established based on the experiment results

Table 1 Formulation and burning rate of two boron-based fuel-rich propellants.

Propellant	HTPB[%]	AP[%]	Catocene[%]	Mg[%]	Al[%]	B[%]	TDI[%]	Burning rate[mm·s^{-1}]			Pressure exponent
								0.1 MPa	0.5 MPa	1.0 MPa	
#1	26.9	35	4	4	4	25	1.1	1.45	3.51	5.0	0.54
#2	26.9	35	4	4	4	25	1.1	1.61	4.27	6.3	0.59

and the Beckstead, Derr, and Price (BDP) combustion model[5].

2. Experimental

2.1 Formulation of boron-based fuel-rich propellant

Two boron-based fuel-rich propellants with the same elemental composition are studied in this paper. Boron used in #1 propellant is the amorphous boron cleaned by toluene diisocyanate (TDI) to improve the consistency of boron and HTPB[5], and boron used in #2 propellant is the amorphous boron coated by 5% AP. The formulation and burning rate of the two propellants are shown in Table 1.

The content of inhaled air in the secondary combustor changes with the flight condition of SFRJ, so the mass flow rate of the gas generator should be adjusted according to the mass flow rate of the inhaled air to make the air-fuel ratio remain constant. For unchoked SFRJ, the nozzle of gas generator is fixed and the flow rate of the gas fuel is adjusted by the different burning rates of the propellant under different pressures, so the pressure exponent of the propellant must be higher enough (usually more than 0.5). As shown in Table 1, the boron coated by AP can increase the pressure exponent of the propellant, which is beneficial to the adjustment of the mass flow rate of the gas generator. Moreover, coating boron with some energetic materials is an effective method to improve the consistency of boron and HTPB[5)-6)], and the content of boron can reach to more than 30 % when the coated boron is used as the raw material of the boron-based fuel-rich propellant.

2.2 Temperature distribution of combustion wave

The propellants were combusted in nitrogen of 1MPa, and the temperature distribution of combustion wave was measured by the fine thermo couple made of Pt/Pt-Rh (R type) with wire diameter of 15 μm. Figure 1 presents the temperature distribution of combustion wave for the two propellants.

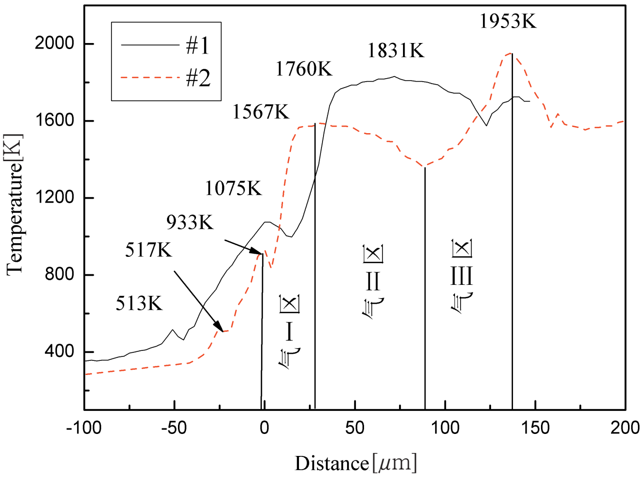


Figure 1 Temperature distribution of combustion wave for two propellants

In general, the combustion process of the propellant can be divided into condensed reaction zone and gaseous reaction zone, and phase transformation of AP is usually considered to be the beginning of the condensed reaction zone. From Figure 1, it can be found that the phase transformation of AP occurs at 513 K and 517 K for the two propellants respectively as shown by the first peak of the two curves, which means the beginning of the condensed reaction zone of the two propellants. Moreover, the combustion surface temperature (T_s) can be considered as the end of the condensed reaction zone (1075 K and 933 K), and the flame temperature (T_f) can be considered as the end of the gaseous reaction zone (1831 K and 1953 K).

From the temperature distribution of the gaseous reaction zone, it can be seen that the structure of gaseous reaction zone of #1 propellant is different from that of #2 propellant. The gaseous reaction zone of #1 propellant can be divided into two subzones while that of #2 propellant can be divided into three subzones. The thickness of different combustion zones for the two propellants (average of three experiments) are shown in Table 2.

For #1 propellant, the temperature increases rapidly and reaches T_1 (1760 K) during the Gaseous I zone, which indicates that the reactions in this zone are mainly exothermic reactions. We hold that the reactions in this zone are mainly vigorous reactions among the decomposition products of AP, HTPB and the reactive metals (magnesium, aluminum and part of boron). Most of the reactions are exothermic reactions and the heat released in this zone is higher than that in other gaseous reaction zones. The thickness of Gaseous II zone is almost the same as that of Gaseous I zone, but the temperature increases slowly in Gaseous II zone because most of the oxidizing gases are consumed in Gaseous I zone and the

Table 2 Thickness of different combustion zones for two propellants.

Propellant	Condensed reaction zone[μm]	Gaseous I zone[μm]	Gaseous II zone[μm]	Gaseous III zone[μm]
#1	39	39	35	–
#2	27	36	66	56

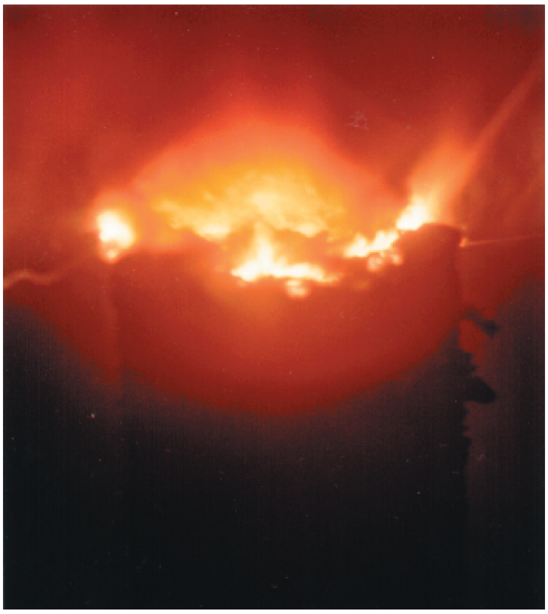


Figure 2 Combustion flame of #1 propellant

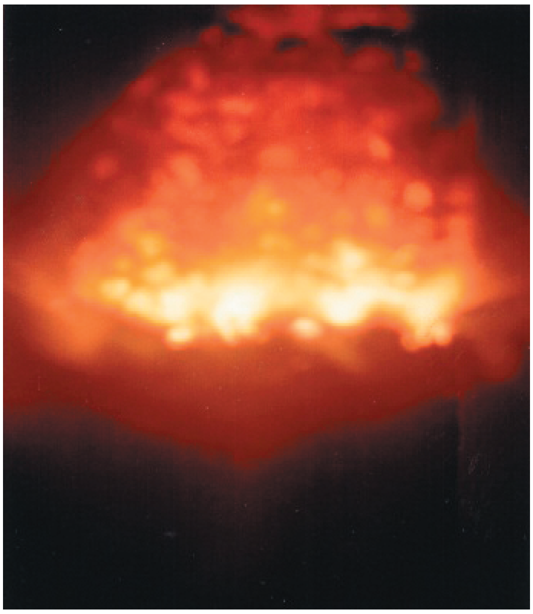


Figure 3 Combustion flame of #2 propellant

oxidation of the fuels proceeds much slower in Gaseous Ⅱ zone. Moreover, although the combustion rate of boron is slower than other fuels, a small part of boron may react with oxidizing gases in the gaseous reaction zone. The boron related reactions in Gaseous Ⅰ zone is mainly the oxidation of boron and boron oxide (B_2O_3) is produced in this zone. As most of the oxidizing gases are consumed in Gaseous Ⅰ zone, boron oxide may react with boron and some boron suboxides $(BO)_n$ are produced in Gaseous Ⅱ zone and the reactions are endothermic which will result in the decrease of the temperature in this zone.

For #2 propellant, the reactions in Gaseous Ⅰ zone are almost the same as that for #1 propellant, but the temperature of this zone is lower. Different from #1 propellant, boron in #2 propellant is in close contact with AP, and AP can decompose at low temperature (about 500 K), which generates oxidizing gases and results in the generation of thicker boron oxide (B_2O_3) film on the surface of boron. Then the reactions between boron and oxidizing gases during Gaseous Ⅰ reaction zone become more difficult, and the heat released in this zone decreases a lot although the combustion heat of boron is very high. The decrease of the temperature in the Gaseous Ⅱ zone indicates endothermic reactions play more important role in this zone, and it is believed that there are two reasons making the temperature decrease, one of which is the formulation of $(BO)_n$, and the other is the evaporation of liquid B_2O_3. With the decrease of the liquid B_2O_3 film, boron will react with small amount of oxidizing gases and generate heat, which leads to the increase of the temperature in the Gaseous Ⅲ zone. In addition, the thermal feedback to the combustion surface is mainly affected by temperature of the gaseous reaction zone, so both T_s and the thickness of condensed reaction zone are affected by the temperature of the gaseous reaction zone. From Figure 1 and Table 2, we can deduce that thermal feedback of #2 propellant is stronger than that of #1 propellant, which also contributes to the increase of the burning rate of #2 propellant.

From the characteristics of combustion wave the conclusion could be made : there is relationship between the primary flame (PF), AP flame, final diffusion flame (FF) of BDP model and the three gaseous zones in this paper. Gaseous reaction zone contains PF and AP flame, Gaseous Ⅱ reaction zone and Gaseous Ⅲ reaction zone are different stages of FF effected by the metal fuel particles (boron, magnesium and aluminum).

Figure 2 and Figure 3 show the images of the combustion flame for the two propellants combusting in nitrogen of 1MPa. It can be seen that the combustion flame is close to the combustion surface and the whole flame consists of a lot of small flames. Besides, there are many bright burning particles on the combustion surface, which indicates that magnesium, aluminum and boron react with the oxidizing gases in the gaseous reaction zone. Compared with #1 propellant, the flame height of #2 propellant is higher and the combustion is more vigorous, so it is reasonable to consider that boron coated with AP can change the combustion process of boron-based fuel-rich propellant.

2.3 Analysis of quenched surfaces

Quenching experiments were carried out in nitrogen of 0.5 MPa, and the quenched surfaces of the two boron-based fuel-rich propellants were analyzed with scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDS). Figure 4 and Figure 5 shows the SEM images of the quenched surfaces for the two propellants, from which we can find the appearance of two quenched surfaces is almost the same, with the characteristics of sags and crests, and irregular porosity. Besides, it should be noticed that the pores of #2 propellant are larger than those of #1 propellant, and the texture of the quenched surface is much looser.

In order to investigate the characteristics of the quenched surface of #2 propellant, Figure 6 presents the

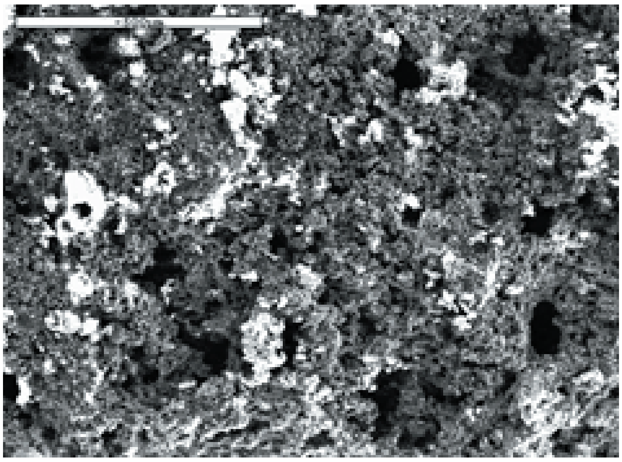


Figure 4 Quenched surface of #1 propellant

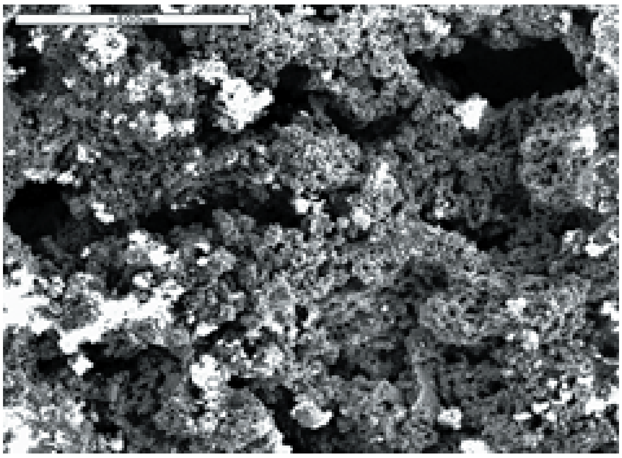
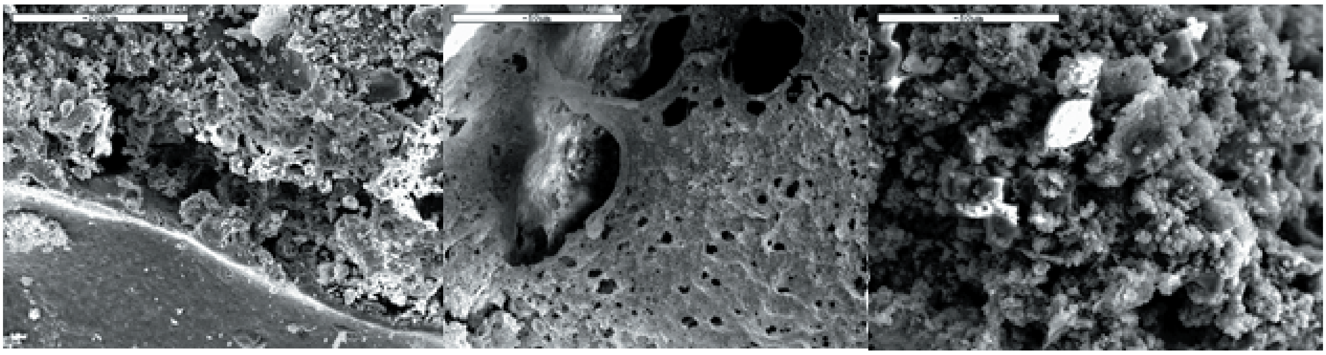


Figure 5 Quenched surface of #2 propellant



(a) (b) (c)

Figure 6 SEM images of quenched surface for #2 propellant.
(a) - cutaway image of the quenched surface (b) - the top layer of (a)
(c) - the bottom layer of (b)

SEM images with higher magnification. Figure 6(a) shows the cutaway image and the boundary between burned propellant and unburned propellant can be found easily. There is a loose "deposit" layer of about 170μm on the combustion surface, and the thickness of the "deposit" is almost the same as that of the gaseous reaction zone mentioned in Section 2.2, which indicates that gaseous phase reactions mainly carry out in the pores of the loose "deposit". Figure 6(b) is the SEM image of "deposit" far away from the combustion surface, and Figure 6(c) is the SEM image of "deposit" near the combustion surface. The two images show that the texture of "deposit" far away from the combustion surface is looser than that near the combustion surface. According to the results of EDS, the loose part is composed of B (about 56 %), C (about 30%), O (10 %), and a small amount of Mg, Al and Fe ; however, in the compact part, the contents of B, Mg, and Al (about 7.6 %, 6.8 %, and 72 % respectively) increase while the content of C (about 10 %) decreases.

The particle size of boron added in the propellant is about 1μm, and the agglomerating of boron almost not appears between the boron particles as the melting point of boron is very high, so the small particles can escape to the loose part of the "deposit" through the small holes. The particle size of magnesium and aluminum is 15μm, and agglomeration is common for the combustion of magnesium and aluminum, so magnesium and aluminum is difficult to reach the loose part of the "deposit" and mainly exists in the location near the burning surface of propellant.

So we can summarize the combustion process of boron-based fuel-rich propellant as follows according to the above experiment results.

(1) The combustion process can be divided into condensed reaction zone and gaseous reaction zone. In condensed reaction zone, only a small part of AP and HTPB decomposes because the decomposition temperature of AP and HTPB is higher than the combustion surface temperature T_s. In Gaseous I reaction zone, reactions among the decomposition products of AP and HTPB, magnesium, aluminum and boron are vigorous and the temperature increases rapidly because the reactions generate a large amount of heat in this zone. Carbon forms near the combustion surface and "deposit" forms with movement of the combustion surface.

(2) Magnesium and aluminum react with oxidizing gases mainly on and near the combustion surface and move slowly from the combustion surface under the reaction of "deposit". As the combustion of magnesium and aluminum releases a large amount of heat, the temperature of combustion surface increases, which results in the higher burning rate and better ignition performance of boron-based fuel-rich propellant. The size of pores has two different effects on the burning rate, on

one hand small pores make the gaseous reaction near the burning surface and the burning rate increases by the increase of heat feedback, on the other hand small pores make the gaseous products escaped from "deposit" more difficult which is disadvantageous to the chemical reactions and the burning rate may decrease by the decrease of reaction heat release.

(3) The gaseous reactions carry out mainly in the pores of "deposit", and the gaseous reaction zone can be divided into three gaseous subzones. In Gaseous Ⅰ zone, the main reactions are vigorous reactions among the decomposition products of AP and HTPB and the reactive metals Mg and Al, and only a small amount of boron reacts with the oxidizing gases because the ignition temperature of boron is high (about 1900 K) and the combustion rate of boron is very slow at low temperature. In Gaseous Ⅱ zone and Gaseous Ⅲ zone, the oxidizing gases have almost been consumed, and only a part of boron reacts and generates heat, so that the thermal feedback to the combustion surface is limited. Thus, the "deposit" can be considered to be inert during the gaseous reaction process.

3. Combustion model of boron-based fuel-rich propellant under low pressure

3.1 Physical model

Through the temperature distribution of combustion wave and quenched combustion experiments, it is found that "deposit" forms on the combustion surface of boron-based fuel-rich propellant, and the products of decomposition cannot escape from the combustion surface freely due to the presence of the "deposit", so the reaction time among them becomes longer, which results in a higher temperature gradient in the gaseous reaction zone. Moreover, the thermal feedback of gaseous reactions to the combustion surface is also strengthened due to the higher thermal conductivity of "deposit" than that of fuel gases, so the combustion surface temperature of boron-based fuel-rich propellant is higher than that of common propellant (about 700K) which may be another reason that boron-based fuel-rich propellant can combust steadily under low pressure.

BDP combustion model is employed to establish the combustion model of boron-based fuel-rich propellant in this paper, and the combustion process can be divided into condensed reaction zone and gaseous reaction zone. The reactions of condensed phases carry out in the condensed reaction zone, and all the released heat is absorbed by the condensed reaction zone. The reactions of gaseous phases carry out in the pores of "deposit" and the heat of reactions can be divided into two parts, one of which is absorbed by the gaseous reaction zone, and the other is the thermal feedback towards the combustion surface through thermal conductivity, convection and thermal radiation. Condensed phase reactions include the decomposition of HTPB and AP, the reactions of boron, magnesium and aluminum with the decomposition products of AP, the reactions of decomposition products of AP and decomposition products of HTPB and so on. Gaseous phase reactions mainly include the reactions among decomposition products of AP and HTPB, magnesium, aluminum and boron near the combustion surface, and the temperature of the gaseous reaction zone increases rapidly to T_f finally.

3.2 Mathematical model

The assumptions of the combustion model are as follows :

(1) The combustion process is quasi-one dimensional and steady, and the location of three flames in the gaseous reaction zone is shown in Figure 7 ;

(2) The condensed reactions mainly occur on the combustion surface ;

(3) The gaseous reactions carry out in the pores of "deposit", and the "deposit" is inert (do not take part in the chmemical reactions) ;

(4) The burning rate of boron-based fuel-rich propellant depends on the decompostion rate of AP and HTPB, especially the decompostion rate of AP on the combustion surface, and the decompostion of AP and HTPB follows Arrhenius law ;

(5) The temperature keeps constant everywhere on the combustion surface ;

(6) Gaseous reactions are simple homogenous reactions ;

(7) The gaseous phases are ideal gases, and the physical parameters of the gas phase (λ, α, D, c) are the average values during the combustion process.

Based on the assumptions above, the formula of burning rate can be obtained by mass conservation equation, energy conservation equation, reaction kinetics equation and physical dimension of propellant.

Generation rate of the gaseous phase products based on mass conservation equation can be expressed as :

$$m=(\alpha+\beta)\rho_p r=m_{\mathrm{HTPB}}\frac{S_{\mathrm{HTPB}}}{S_0}+m_{OX}\frac{S_{OX}}{S_0}, \tag{1}$$

where m_{HTPB} and m_{OX} are mass flow rates of HTPB and AP per unit combustion area respectively, S_0 is the combustion area of the propellant, S_{HTPB} and S_{OX} are the decomposition surface area of HTPB and AP respectively, and α and β are the mass fraction of AP and HTPB in the propellant respectively.

Assuming that the mass of decomposed AP is equal to that of decomposed HTPB on the combustion surface, then

$$\frac{\mathrm{m}_{OX}\,(S_{OX}/S_0)}{m_{\mathrm{HTPB}}\,(S_{\mathrm{HTPB}}/S_0)}=\frac{\alpha}{\beta}, \tag{2}$$

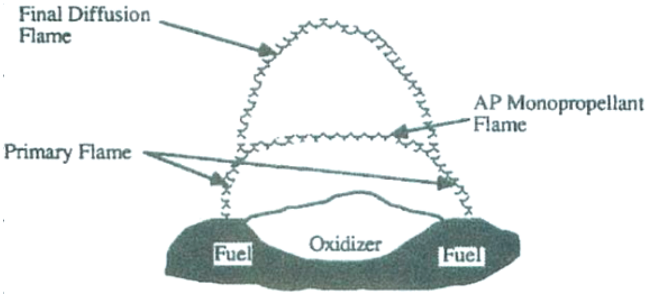


Figure 7 Flame structure of quasi-one dimension

and we can get Equation (3) from Equations (1) and (2) as follows:

$$r=\frac{1}{\beta\cdot\rho_p}\cdot m_{\mathrm{HTPB}}\cdot\frac{S_{\mathrm{HTPB}}}{S_0}=\frac{1}{\alpha\cdot\rho_p}\cdot m_{OX}\cdot\frac{S_{OX}}{S_0}. \tag{3}$$

As we assume the burning rate of the propellant depends on the decomposition rate of AP, the formula of the burning rate can be expressed as:

$$r=\frac{1}{\alpha\cdot\rho_p}\cdot m_{OX}\cdot\frac{S_{OX}}{S_0}, \tag{4}$$

and m_{OX} can be determined through Arrhenius law as:

$$m_{\mathrm{OX}}=\mathrm{A}_{\mathrm{OX}}\exp\left(-\frac{E_{OX}}{R_0T_s}\right). \tag{5}$$

According to the assumptions, the heat that makes combustion surface temperature increase from initial temperature T_0 to combustion surface temperature T_s is equal to the sum of the condensed phase reaction heat and the thermal feedback of the gaseous phase reaction to the combustion surface. Assuming that the heat release of the three flames concentrates on their corresponding flame shell, the energy balance equation of the combustion surface can be expressed as:

$$\begin{aligned}&mS_0c_{\mathrm{P}}(T_{\mathrm{s}}-T_0)-mS_0Q_s\\&=\beta_{\mathrm{F}}(\alpha+\beta)\,\mathrm{m}S_0Q_{PF}\exp(-\xi^*_{PF})+(1-\beta_{\mathrm{F}})\,m_{\mathrm{OX}}\mathrm{S}_{\mathrm{OX}}\\&\left[Q_{AP}\exp(-\xi^*_{AP})+Q_{FF}\exp(-\xi^*_{FF})\right].\end{aligned} \tag{6}$$

So

$$\begin{aligned}&T_{\mathrm{s}}T_0+\frac{Q_s}{c_{\mathrm{P}}}+\beta_F(\alpha+\beta)\frac{Q_{PF}}{c_{\mathrm{P}}}\exp(-\xi^*_{PF})+(1-\beta_F)\,\alpha\\&\left[\frac{Q_{AP}}{c_{\mathrm{P}}}\exp(-\xi^*_{AP})+\frac{Q_{FF}}{c_{\mathrm{P}}}\exp(-\xi^*_{FF})\right],\end{aligned} \tag{7}$$

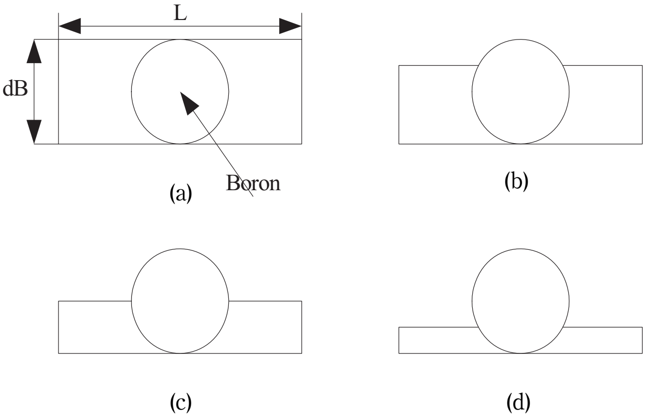
where Q_s is the heat of condensed reaction, Q_{PF}, Q_{AP} and Q_{FF} are the heat of reaction of PF, AP flame and FF respectively, C_{P} is the specific heat of the propellant, β_{F} is the mass fraction of oxidizing gaseous reacting with HTPB, and ξ^*_{PF}, ξ^*_{AP} and ξ^*_{FF} are the non-dimensional projection distance of the flames respectively.

The non-dimensional projection distance of the flame can be expressed as:

$$\left.\begin{aligned}\xi^*_{\mathrm{AP}}&=\frac{c_{\mathrm{P}}m_{OX}}{\lambda}X^*_{AP}\\\xi^*_{PF}&=\frac{c_Pm}{\lambda}X^*_{PF}\\\xi^*_{FF}&=\frac{c_Pm_{OX}}{\lambda}X^*_{FF}\end{aligned}\right\}, \tag{8}$$

where X^*_{PF}, X^*_{AP} and X^*_{FF} are the distance of PF, AP flame and FF away from the combustion surface respectively.

To get the value of (S_{OX}/S_0), effect of the content of boron in boron-based fuel-rich propellant must be considered. In order to make the result simple, we assume that the propellant is the mixture of boron and HTPB, and the combustion of HTPB follows the parallel layer rule. For unit volume of propellant composed of boron and HTPB, the number of boron particles $n=\dfrac{\xi_B}{\frac{\pi d_B^3}{6}(\xi_B+\xi_{HTPB})}$, where ξ_{HTPB} and ξ_{B} are the volume fractions of HTPB and boron in the propellant respectively.



(a) (b)
(c) (d)

Figure 8 Moving surface of boron and HTPB

Assuming the unit volume of propellant is a cube element, if the cube element is divided into $1/d_{\mathrm{B}}$ equal segments according to the thickness of the cube, the thickness of each segment is d_{B}, and the number of boron particles in each segment $n'=\dfrac{\xi_B}{\frac{\pi d_B^2}{6}(\xi_B+\xi_{HTPB})}$.

The surface area change of boron and HTPB during the decomposition of HTPB is shown in Figure 8, and the average surface areas of boron and HTPB during the decomposition of HTPB are:

$$\mathrm{S}_{\mathrm{B}}=\frac{1}{2}\pi d_{\mathrm{B}}^2, \tag{9}$$

$$\mathrm{S}_{\mathrm{B}}^{\mathrm{P}}=\frac{1}{6}\pi d_{\mathrm{B}}^2, \tag{10}$$

$$\mathrm{S}_{\mathrm{HTPH}}=\mathrm{d}_{\mathrm{B}}\times\mathrm{L}-\frac{\pi}{6}\mathrm{d}_{\mathrm{B}}^2, \tag{11}$$

where SHTPB and SB are average area of HTPB and boron during the combustion of HTPB respectively, and $\mathrm{S}_{\mathrm{B}}^{\mathrm{P}}$ is the average projection area of the boron on the combustion surface. Then

$$\frac{\xi_{\mathrm{HTPB}}}{\xi_{\mathrm{B}}}=\frac{\mathrm{n}\left(\mathrm{L}\times\mathrm{d}_{\mathrm{B}}^2-\frac{\pi}{6}\mathrm{d}_{\mathrm{B}}^3\right)}{\mathrm{n}\times\frac{\pi}{6}\mathrm{d}_{\mathrm{B}}^3}=\frac{S_{HTPB}}{S_B^P}, \tag{12}$$

and

$$\mathrm{L}=\frac{\pi}{6}\mathrm{d}_{\mathrm{B}}\left(\frac{\xi_{\mathrm{HTPB}}}{\xi_{\mathrm{B}}}+1\right). \tag{13}$$

From Equations (9) (13), $S_{\mathrm{HTPB}}/S_{\mathrm{B}}$ can be determined as:

$$\frac{\mathrm{S}_{\mathrm{HTPB}}}{\mathrm{S}_B}=\frac{1}{3}\frac{\xi_{\mathrm{HTPB}}}{\xi_B}. \tag{14}$$

It is known that there is convex AP in the combustion surface during the combustion of the composite propellant when the pressure is less than 4.2 MPa, and the convex AP will affect the area of the combustion surface. According to References7),8), it can be obtained

$$\frac{\mathrm{S}_{\mathrm{OX}}}{\mathrm{S}_{\mathrm{OX}}^{\mathrm{P}}}=1+6\left(\frac{\mathrm{h}}{\mathrm{D}_0}\right)^2, \tag{15}$$

where S_{OX} is the average surface area of AP during the combustion of propellant, and $\mathrm{S}_{\mathrm{OX}}^{\mathrm{P}}$ is the average projection area of AP on the combustion surface.

The average surface area of the fuel is the sum of average surface areas of boron and HTPB, so

$$S_0 = S_{OX} + S_{HTPB} + S_B, \tag{16}$$

and

$$\zeta_{OX} = \frac{S_{OX}^{P}}{S_{OX}^{P} + S_{HTPB} + S_{B}^{P}}\,. \tag{17}$$

From Equations (12) and (14), and Equations (15), (17), S_{OX}/S_0 can be obtained as :

$$\frac{S_{OX}}{S_0} = \frac{\xi_{OX}\left[1+6\left(h/D_0\right)^2\right]}{\xi_{OX}\left[1+6\left(h/D_0\right)^2\right]+\left(\xi_{HTPB}+3\xi_B\right)}\,. \tag{18}$$

3.3 Discussion and analysis of the combustion model

The escape of fuels and oxidizer on the combustion surface is limited because of the inert "deposit", so the flow rate of the fuels and oxidizer in the gaseous reaction zone is lower. On one hand, the lower flow rate of the gaseous phase will result in the decrease of X_{PF}^{*}, X_{AP}^{*} and X_{FF}^{*}[6), 7)], and on the other hand, the thermal conductivity of "deposit" is better than that of gases, which means the λ in Equation (8)increases. Consequently, the second and third terms in the right side of Equation (7) increase, which results in the increase of the combustion surface temperature T_s. Compared with common composite propellant, the pressure exponent for boron-based fuel-rich propellant under low pressure is higher as the "deposit" strengthens the gaseous reaction.

The content of AP (usually about 30%) is low in boron-based fuel-rich propellant, and the burning rate of the propellant decreases with the decrease of AP because the combustion heat decreases and the heat absorbed by other materials (boron, magnesium, aluminum, et al.) increases. For boron-based fuel-rich propellant, most boron does not react with the other materials, but boron cannot keep the combustion surface from movement. As mentioned above, combustion surface temperature T_s increases due to the formation of "deposit", and from Equations (4) and (5), we can find that the burning rate of propellant decreases exponentially with the increase of T_s, so the burning rate of boron-based fuel-rich propellant can be high under low pressure.

Moreover, according to Equation (18), S_{OX}/S_0 will decrease with the increase of boron, and this will result in the decrease of the burning rate of the boron-based fuel-rich propellant as Equation (4) indicates.

4. Conclusions

In summary, the combustion mechanism of boron-based fuel-rich propellant under low pressure was investigated in this paper, and a combustion model was proposed based on BDP combustion model to interpret the combustion characteristics. Some conclusions can be drawn as follows :

(1) Coating boron with AP for boron-based fuel-rich propellant can increase the burning rate, pressure exponent and combustion surface temperature of the boron-based fuel-rich propellant under the low pressure, while make the combustion process of the propellant more complicated.

(2) "Deposit" forms when the boron-based fuel-rich propellant combusts under low pressure, and the combustion process can be divided into condensed reaction zone and gaseous reaction zone. Condensed phase reaction carries out in the condensed phase while gaseous phase reaction carries out mainly in the pores of "deposit".

(3) A combustion model of boron-based fuel-rich propellant under low pressure is established based on the BDP combustion model, which assumes the reaction of boron with AP occurs in the condensed phase zone and that "deposit" forms on the combustion surface of the propellant in the gaseous zone. The results of the model indicate that the "deposit" not only makes boron-based fuel-rich propellant combust steadily but also increases the burning rate and pressure exponent of boron-based fuel-rich propellant under low pressure by strengthening the thermal feedback of the gaseous reaction zone to the combustion surface.

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