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Experimental Study on Combustion Process of NEPE Propellant

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Abstract

To elaborate the combustion mechanism and provide data support for combustion models of Nitrate Ester Plasticized Polyether (NEPE), an experimental system was built to study the combustion characteristics of four kinds of NEPE propellant. Combustion process and flame characteristic were observed and burning rate, temperature of combustion surface and burning rate pressure exponent could be obtained. The results showed the impact of backpressure and grain size on flame structure, burning rate and burning rate pressure exponent. Then the predominant reaction in different period of combustion process could be found.

1. Introduction

Since solid propellant is the main energy source for solid rocket motor, the increase of specific impulse has always been a main aim during its development. Nitrate Ester Plasticized Polyether (NEPE) is a significant breakthrough of high-energy solid propellant. It combines advantages of composite propellant and double base propellant, which means that it has both high energy and good mechanical property. Nitrate ester energetic plasticizer is employed instead of inert plasticizer in NEPE such as NG, BTTN and so on. Besides, nitramine explosive such as HMX, RDX and TAGN is employed to replace AP as oxidizer to increase energy and reduce smog. NEPE has the highest specific impulse among solid propellants that have been in application in the world. Its standard theoretical specific impulse could reach to 2685N·s/kg and its density could reach to 1.86g/cm^3 [1].
Current studies on combustion characteristics focus mainly on the structure of flame, the characteristics of binder, the law of burning rate and burning rate pressure exponent, and the burning rate regulator: (1) AP would cause the flame structure closer to diffusion flame. The energetic polymers would dissolve AP, then the mixture of AP dissolved and the gaseous product of binder would cause the formation of premixed flame. (2) The burning rate pressure exponent of binder is high. The energy of binder is also an important factor to the burning rate. (3) AP is dominant to the burning rate of NEPE propellant and the grain size of AP has more impact on the burning rate pressure exponent compared with HMX. The burning rate would increase when the grain size of AP is smaller. The relation of burning rate and burning rate pressure exponent fits the Vielle burning rate equation well. The relative amounts of HMX/Aluminum and Aluminum/AP have less impact on the combustion characteristics of NEPE propellant compared with the relative amount of HMX/AP within a certain range. The relative increase of AP and relative decrease of HMX would cause the increase of burning rate and the decrease of burning rate pressure exponent. Spherical aluminum particles would cause a lower burning rate pressure exponent compared with non-spherical aluminum particles. (4) The common regulator for traditional cannot be employed for NEPE propellant [4-7].
Although a number of papers have been published in the general area of combustion law of NEPE propellant, the combustion mechanism and the influence on the combustion process of different ingredients have not yet been thoroughly investigated. Besides, there is no generally accepted combustion model of NEPE propellant up to now.
This study is focused on the impact of backpressure, composition formula and grain size on the combustion characteristics of NEPE propellant. An important objective of this study is to lay a foundation for the establishment of combustion model of NEPE propellant. This paper begins with a short description of the experimental scheme. Then results of experimental testing are provided and discussed. Finally several conclusions are drawn from the study.

2. Experimental Method

2.1 Experimental Scheme

An overall diagram of the apparatus is given in figure 1. The experiment system consists of the vacuum chamber, the resistance wire ignition system, the gas supply system, the control and measuring system and the high-speed photography system. All combustion tests were conducted in a vacuum chamber under nitrogen atmosphere. The test

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sample was fixed on the tungsten-rhenium thermocouple with its top near the resistance wire. The pressure in the vacuum chamber and the temperature of the test sample were measured and recorded during the whole experiment. The combustion process was observed and recorded by the high-speed camera. The frame frequency of the high-speed camera was set to be 1000Hz, while the time of exposure was 50μm for no-Aluminum-contained NEPE propellant and 10μm for Aluminum-contained NEPE propellant, since the flame might be brighter because of the combustion of Aluminum.

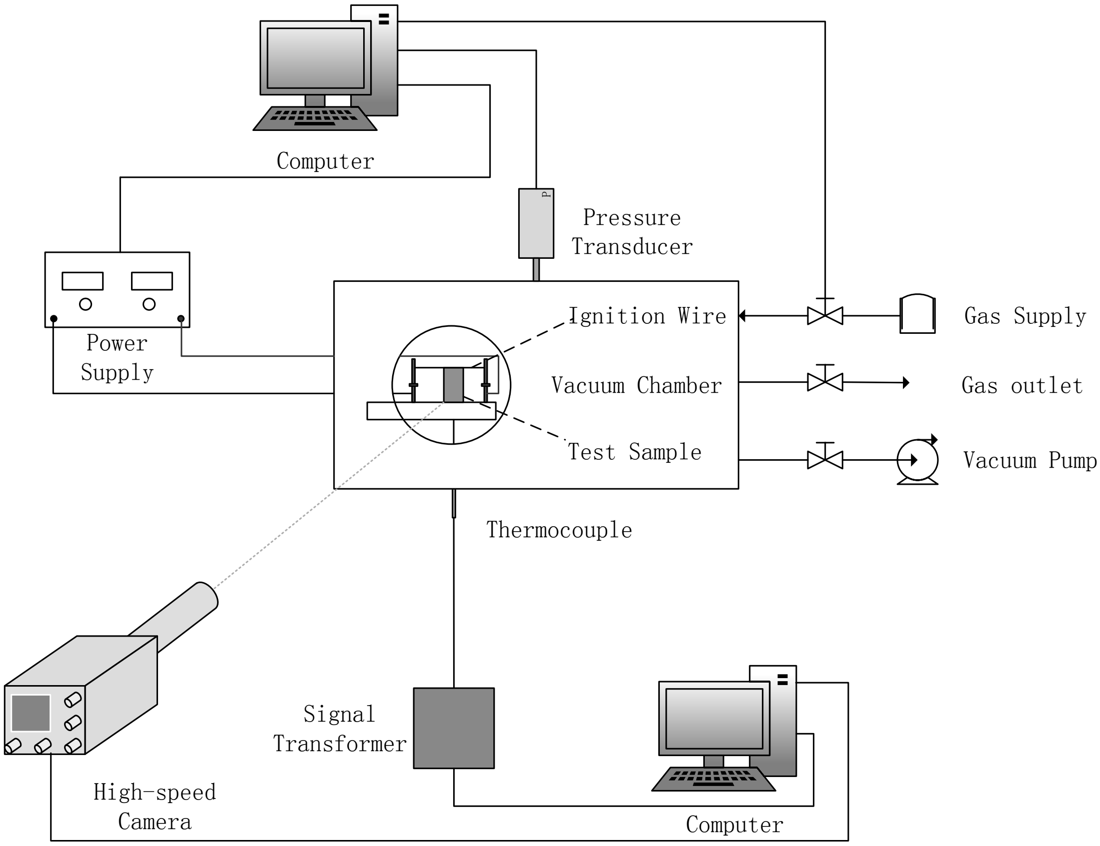

Figure 1. Experimental setup

2.2 Propellant Formulations

Figure 2 shows four kinds of NEPE propellants that were utilized in the experiment. It is easy to cut them into samples with required size since they all have low hardness. The test samples in this experiment were typically 5mm×5mm×7mm rectangular bars. To obtain end burning, we dissolved PVB in absolute ethyl alcohol by heating and stirring, and then coated the test samples with this mixture as fire retardant. Consequently, the experimental phenomenon would be clearer and easier to observe.

Figure 2. Test NEPE solid propellants

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Table 1 shows ingredients, weight mixture ratio and grain size of four kinds of test NEPE propellant. All of them contain two kinds of oxidizer, ammonia perchlorate (AP) and HMX. Only KD-3 and KD-4 contain Aluminum. Binder is made of PEG (25%) and plasticizer (75%), while plasticizer is made of NG (50%) and BTTN (50%). KD-1 and KD-2 have the same weight percentage of AP, HMX and binder. But KD-1 has bimodal AP distribution (130μm and 13μm) while KD-2 has bimodal HMX distribution (86μm and 12μm). Similarly, KD-3 and KD-4 have the same weight percentage of AP, HMX, Aluminum and binder, while KD-3 has bimodal AP distribution (130μm and 13μm) as well as bimodal HMX distribution (86μm and 12μm) and KD-4 has bimodal Aluminum distribution (28μm and 3μm).

Table 1. Ingredients, weight mixture ratio and grain size of test NEPE propellants

Propellant Name	**AP-1/% (130μm)**	**AP-2/% (13μm)**	**HMX-1/% (86μm)**	**HMX-2/% (12μm)**	**Al-1/% (28μm)**	**Al-2/% (3μm)**	**Binder/%**
KD-1	10	10	48	\	\	\	32
KD-2	20	\	24	24	\	\	32
KD-3	8	8	20	20	18	\	26
KD-4	16	\	40	\	9	9	26

2.3 Vacuum Chamber

The vacuum chamber is cylindrical with a diameter of 216mm and a height of 350mm. The stainless steel wall has a thickness of 8mm and it can bear a pressure not lower than 4MPa. There are two 80mm-diam windows on the vacuum chamber for monitoring the combustion process. The vacuum chamber is connected to three valves including an exhaust valve connected to vacuum pump, an exhaust valve connected to the external environment, and a nitrogen valve connected to the gas supply system. By controlling these valves, the backpressure of the vacuum chamber is variable from 0Mpa to 3MPa. A pressure sensor and a thermocouple were arranged in the chamber through measuring interfaces so that the pressure in the chamber and the temperature of the test sample and the flame could be measured during combustion.

2.4 Resistance wire ignition system

Nichrome wire showed in figure 3 was used as ignition wire. Figure 4 shows the power supply used in this experiment to supply power for ignition. Tested NEPE propellants are inflammable because of the high content of oxidizer. As a result, we made ignition wire out of touch with the surface of test sample to reduce its interference with ignition and combustion since the heat that ignition wire radiate before fusing is enough to ignite the test sample. The test before the formal experiment showed that ignition could happen within several seconds after power on and the ignition wire could fuse quickly. It could be seen that ignition wire has little influence on ignition and combustion.

Figure 3. Ignition wire

Figure 4. Power supply

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2.5 Gas supply system

Pressure-feed providing system was utilized to supply gas including air, nitrogen, oxygen, hydrogen *et al*. for the vacuum chamber. The highest pressure it can provide is 4MPa. Required atmosphere and pressure could be achieved by using valves of the gas distribution board. The pressure in the vacuum chamber is a little lower than the pressure showed on the pressure gage of the gas distribution board because of the error in the pipes.

2.6 Control and measurement system

Control and measurement system consists of two parts, control platform and temperature measurement system. After the preparation of the experiment, the experimental sequence could be set by computer of the control platform. During the experiment the control platform would control the switch of the gas supply system and the relay, then it could control the gas supply process and the ignition process, and the change of pressure in the vacuum chamber could be measured.
Temperature measurement system consists of tungsten-rhenium thermocouple, signal converter and computer. Figure 5 shows a tungsten-rhenium thermocouple used in this experiment. Its filament diameter is 0.2mm and its contact diameter is about 0.5mm. The measuring range is from 0 to 2300 degree centigrade and the measuring error is ±5%. The frequency of data collection is 20Hz and the data can be displayed and recorded in real time.

Figure 5. Tungsten-rhenium thermocouple

Figure 6. High-speed camera

2.7 High-speed photography system

High-speed photography system was used to observe and record the combustion process. It consists of the high-speed camera, the microscopic lens and the computer. The high-speed camera we used in this experiment is PCO.dimax S4 made by HS VISION Company in Germany, showed in Figure 6. The parameter of the microscopic zoom lens from Japan's Nikon is 24-85mm, f/2.8-4D. The computer is used to observe and record the experiment process for the following analysis.

3. Results

3.1 Flame Characteristic

Figure 7 shows how flame characteristic of no-Aluminum-contained NEPE propellant transformed during the combustion process. Under heating from the resistance wire, the gasification and thermal decomposition began first on the surface of the propellant, and initial flame appeared. The self-sustaining combustion would maintain after resistance wire fusing. The dark zone would disappear since the content of AP was high and its flame would be dominant. During the combustion process, there would be particles escaped from the surface which were brighter than the flame. A possible explanation for this is that they were burning AP particles that escaped from the surface because of the gas generated by thermal decomposition.
In the initial and middle stage of combustion, there was typical diffusion flame since the flame of different component was independent from each other. The molten layer was observed clearly on the surface in the ignition experiment before, of which the main compositions were molten blends of nitramine and energetic binder. Since they have the same chemical composition and flame structure, the flame would turn into premixed flame in the final stage of combustion, which was thin, long and steady. There would still be molten layer existed which was pretty thick.

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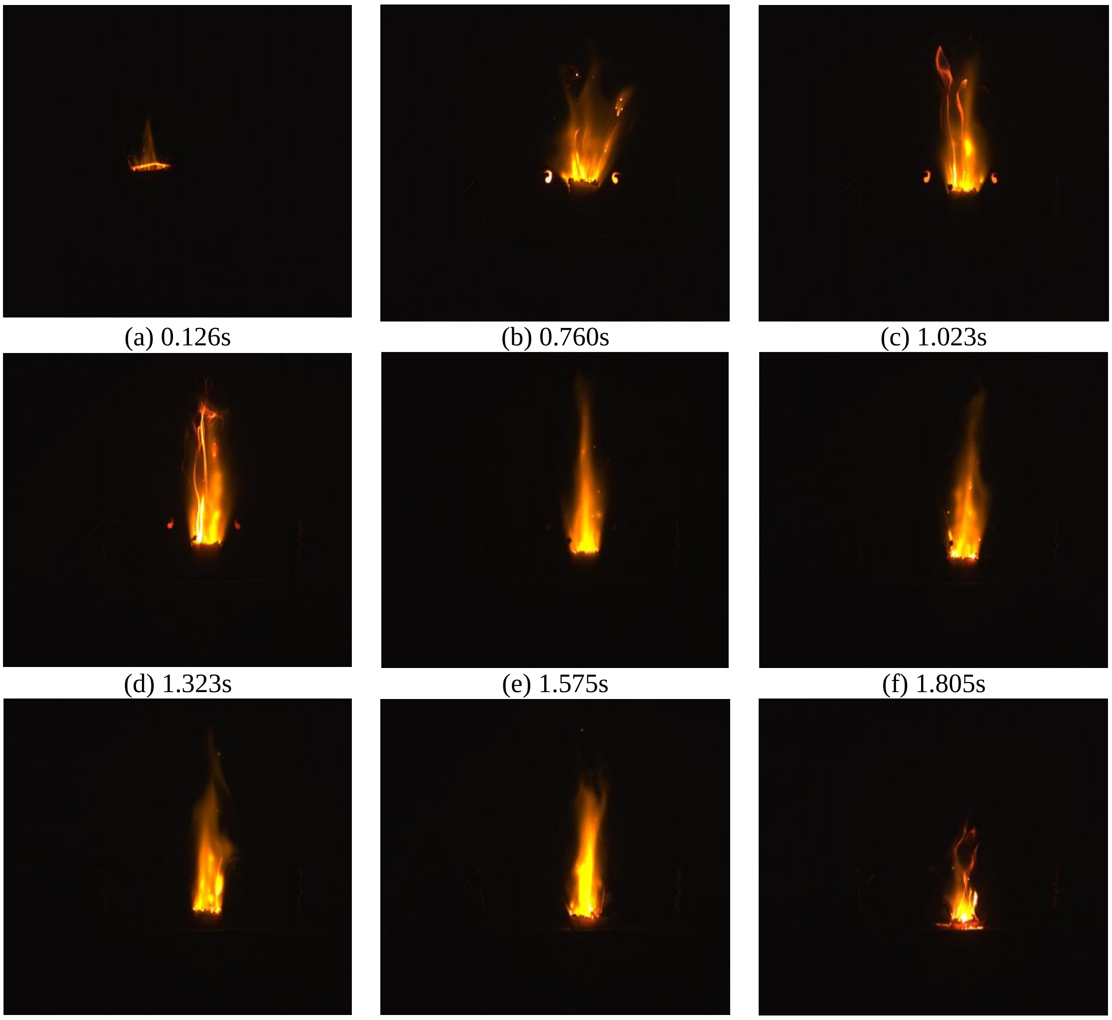

(a) 0.126s (b) 0.760s (c) 1.023s

(d) 1.323s (e) 1.575s (f) 1.805s

(g) 2.090s (h) 2.285s (i) 2.505s

Figure 7. Flame change of KD-1 during combustion under 1.475MPa

Figure 8 shows how flame characteristic of Aluminum-contained NEPE propellant transformed during the combustion process. The flame would be much brighter after aluminum particles were added. White lightspots appeared on the surface first, then they escaped from the surface and entered the gas-phase flame, and finally they would disappear. It is suggested that Aluminum particles in the propellant would melt and initial combustion would happen on the surface. Then they escaped from the surface because of the gas generated by gasification and thermal decomposition, and further combustion would happen in the gas phase away from the burning surface, which would cause the gas-phase flame bright. There would be enough oxidizer as the reaction continued, which guaranteed the sufficient burning of Aluminum particles in the gas phase. Therefore the flame would become bright and homogeneous, and no dark zone but the molten layer existed. Compared with no-Aluminum-contained NEPE propellant, there was smog in quantity during the combustion of Aluminum-contained NEPE propellant, which was caused by the combustion of Aluminum particles.

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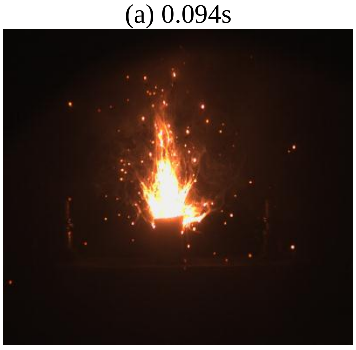
(a) 0.094s

(b) 0.244s

(c) 0.384s

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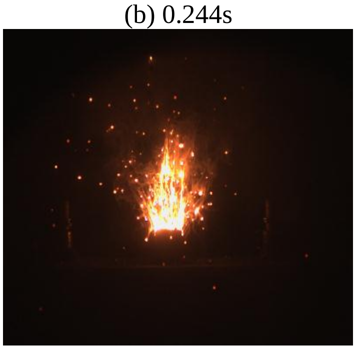
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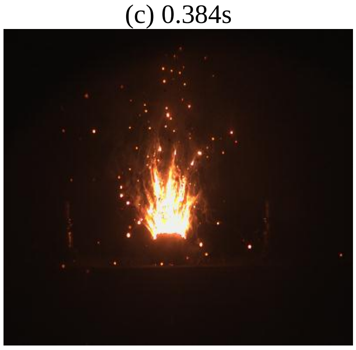
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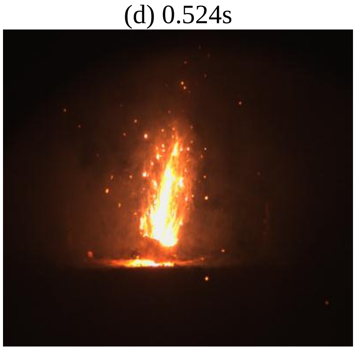
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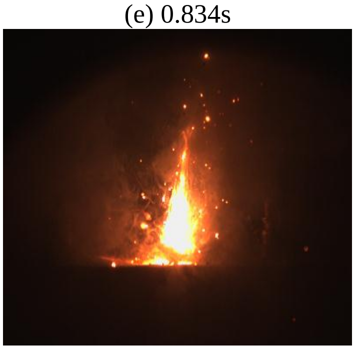
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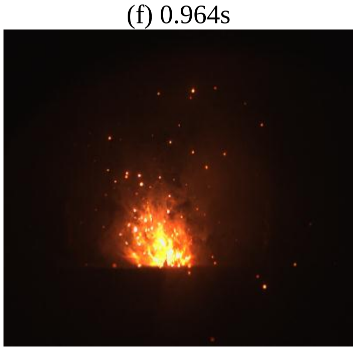
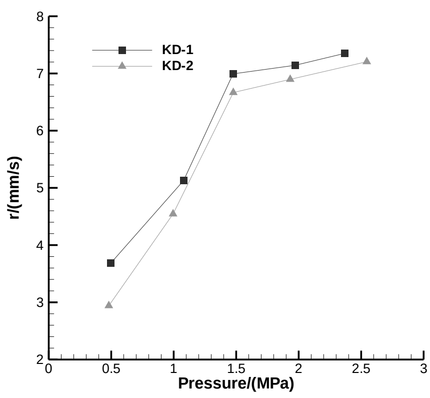

(i) 1.464s

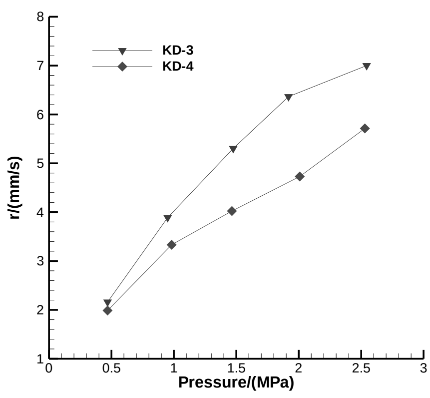
Figure 8. Flame change of KD-4 during combustion under 2.008

3.2 Impact of Backpressure on Combustion

Tests were conducted under 5 kinds of backpressure for all four kinds of NEPE propellant. Figure 9 shows how burning rate changed with pressure for each NEPE propellant. It could be seen that the burning rate would increase as the pressure increase, but the increasing range would reduce. But anyway it has to be pointed out that in one test under 1.5MPa KD-1 burned with a similar burning rate with KD-1 under 0.5MPa and the reason were not clear.



(a) No-Aluminum-contained NEPE propellant



(b) Aluminum-contained NEPE propellant

Figure 9. Burning rates vs. pressure

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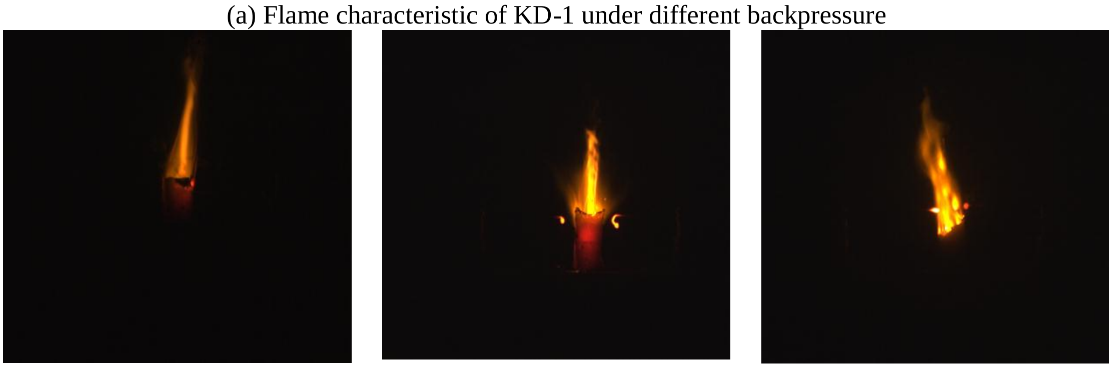
Figure 10 shows the flame structure of test propellant at the same reaction stage under different backpressure. It could be seen that for no-Aluminum-contained NEPE propellant, when the backpressure increased, the gas-phase flame would become more homogeneous and brighter, the diffusion flame would be more obvious, and the combustion characteristic of AP composite propellant would be more obvious. For Aluminum-contained NEPE propellant, when the backpressure increased, the reaction speed would increase, the release of heat in the reaction zone would be severer, and the flame would also be more homogeneous and brighter.

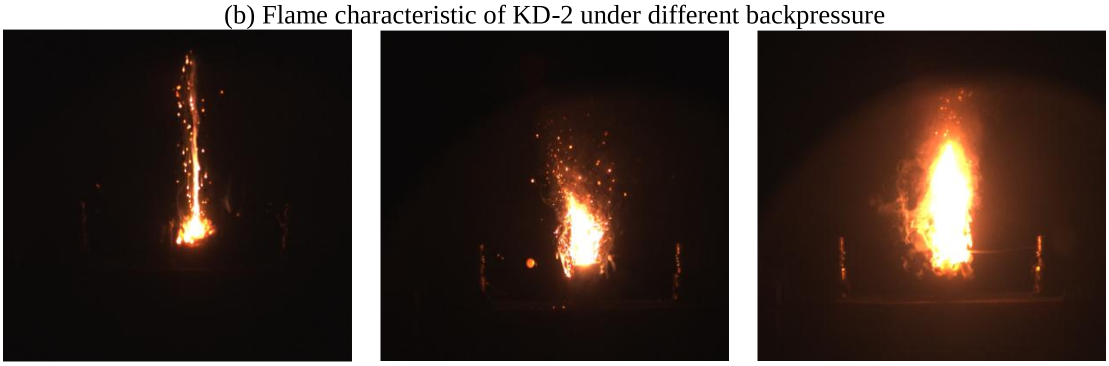
(1) 0.496MPa (2) 1.475MPa (3) 2.37MPa

(a) Flame characteristic of KD-1 under different backpressure



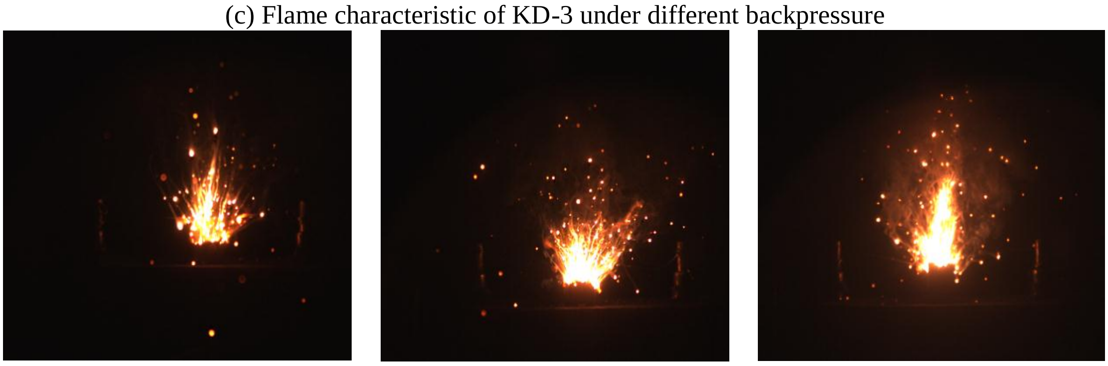
(1) 0.481MPa (2) 1.477MPa (3) 2.545MPa

(b) Flame characteristic of KD-2 under different backpressure



(1) 0.469MPa (2) 1.475MPa (3) 2.544MPa

(c) Flame characteristic of KD-3 under different backpressure



(1) 0.469MPa (2) 1.465MPa (3) 2.53MPa

(d) Flame characteristic of KD-4 under different backpressure

Figure 10. Flame characteristic of NEPE propellant under different backpressure

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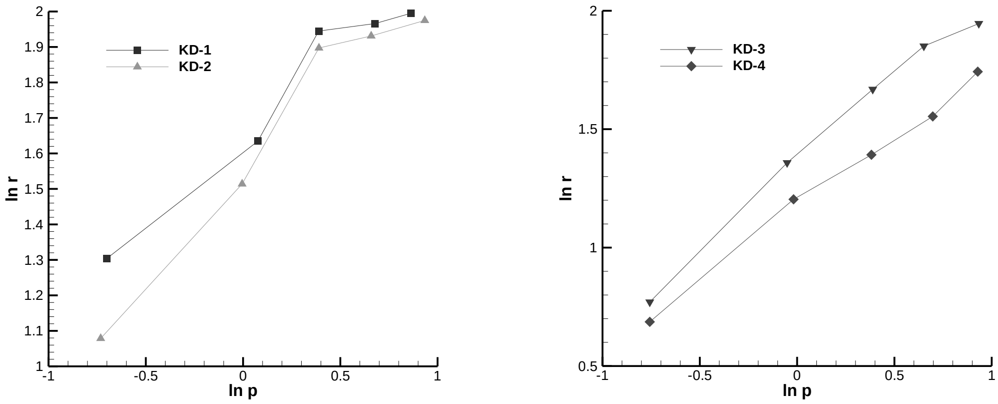
3.3 Impact of ingredients and grain size on combustion

It could be seen in figure 9 that for no-Aluminum-contained NEPE, the burning rate of KD-1 was always higher than KD-2 under the same backpressure. Table 1 shows that KD-1 and KD-2 have the same ingredients, but different grain size. KD-1 contains AP of smaller grain size while KD-2 contains HMX of smaller grain size. It is known that the decrease of grain size of both AP and HMX would cause the increase of burning rate. So it could be analyzed to know that the grain size of AP had more impact on burning rate than HMX as for oxidizer.

As for Aluminum-contained NEPE propellant, the burning rate of KD-3 was always higher than KD-4 under the same backpressure. Similarly, it could be found from table 1 that KD-3 and KD-4 have the same ingredients, but different grain size. KD-3 contains AP and HMX of smaller grain size while KD-4 contains Aluminum of smaller grain size. The decrease of grain size of Aluminum would also cause the increase of burning rate. It could be suggested that the grain size of oxidizer would impact more on burning rate than Aluminum.

Figure 11 shows ln p-ln r curves for these four kinds of NEPE propellant. The slope of the curve would be the burning rate pressure exponent of the propellant according to the Vielle burning rate equation. It could be seen that the burning rate pressure exponent of KD-1 was lower than KD-2, which suggests that the decrease of grain size of AP could decrease the burning rate pressure exponent more effectively compared with HMX. Similarly, the burning rate pressure exponent of KD-3 was higher than KD-4, which suggests that the decrease of grain size of Aluminum particles would decrease the burning rate pressure exponent more effectively compared with oxidizer.

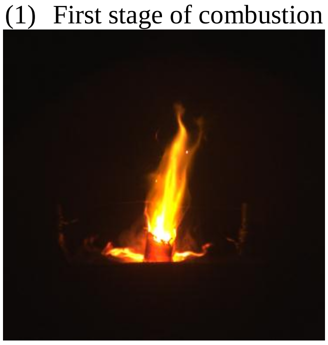


(a) NEPE propellant contains no Aluminum (b) NEPE propellant contains Aluminum

Figure 11. ln r vs. ln p

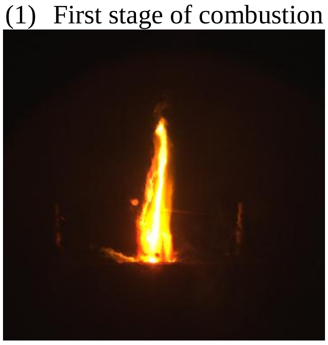
(1) First stage of combustion

(1) First stage of combustion



(2) Final stage of combustion

(a) KD-1



(2) Final stage of combustion

(b) KD-2

Figure 12. Flame characteristic of KD-1 and KD-2 under 2MPa backpressure

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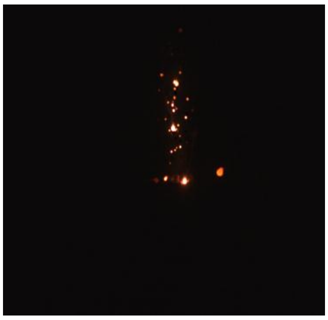
Figure 12 shows the flames of KD-1 and KD-2 in the initial stage and the final stage of the combustion process under 2MPa backpressure. The flame structures were basically the same, all diffusion flames in the initial stage and premixed flames in the final stage, which suggests that the grain size of neither AP nor HMX would impact too much on the flame characteristic. In the first stage, the flame of KD-1 was smaller compared with KD-2, while the characteristic of premixed flame was more obvious for KD-2 since the flame was thinner and longer. The reason might be that AP particles with smaller grain size in KD-1 would gasify, decompose and then combust near the burning surface more quickly. Then the flame would be closer to the burning surface. KD-2 contains HMX with smaller grain size, which caused the faster formation of molten blends in the molten layer, then the faster transformation from diffusion flame to premixed flame. Combining it with burning rates of KD-1 and KD-2, it might be suggested that the decomposition of AP would have more impact on the combustion process compared with the molten blends in the final stage of combustion, which was to say that the gas-phase reaction zone would dominate the combustion process.

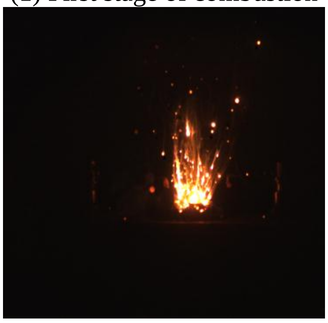


(1) First stage of combustion

(1) First stage of combustion

(2) Final stage of combustion

KD-3



(2) Final stage of combustion

KD-4

Figure 13. Flame characteristic of KD-3 and KD-4 under 2MPa backpressure

Figure 13 shows the flames of KD-3 and KD-4 in the initial stage and the final stage of the combustion process under 0.469MPa backpressure. It could be found that in the first stage of combustion, there were more Aluminum particles escaped from the surface of KD-4, besides it showed a broader distribution of Aluminum particles in the gas phase for KD-4. In the final stage, the flame of KD-3 was thinner and longer ant it had more characteristic of premixed flame. The reason might be that in the first stage, Aluminum particles with smaller grain size in KD-4 were easier to escape from the surface under the effect of gas flow and had a broader range for movement. Besides Aluminum particles with smaller grain size were easier to combust, which caused the flame of KD-4 brighter than KD-3. In the final stage of combustion process, the molten blends of nitramine and energetic binder would be dominant gradually. KD-3 would have a more obvious premixed flame compared with KD-4 since KD-3 contains HMX with smaller grain size, which was easier to decompose. Combining it with burning rates of KD-3 and KD-4, it could be suggested that the molten blends in the final stage had more impact on the combustion process, which would also explain why the grain size of Aluminum had more impact on ignition delay time but less impact on burning rate compared with the grain size of oxidizer.

Table 2. Temperature on the burning surface under approximate backpressure

NEPE Propellant	**KD-1**	**KD-2**	**KD-3**	**KD-4**
Pressure（MPa）	0.496	0.481	0.469	0.469
Burning surface temperature（℃）	380	478	456	692

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Since the error of backpressure was less than 5%, it could be approximately considered that table 2 shows the temperature on the burning surface of four kinds of NEPE propellant under the same backpressure. Since the temperature presented dramatic changes and the frequency of the thermocouple to collect data might not be high enough, the temperature might not be the exact burning surface temperature, but just show the trend. It could be found that after the addition of Aluminum particles with small grain size, the burning surface temperature would increase obviously. Combining it with the flame structure, it could be suggested that although some physical changes happened on the burning surface would absorb heat such as preheat, rupture of oxidation film, and fusion, the heat generated by the initial combustion of Aluminum particles on the burning surface and the combustion of Aluminum particles in the gas-phase zone near the burning surface might still be transferred to the burning surface and cause the increase of the burning surface temperature. The decrease of grain size of Aluminum had more impact on burning surface temperature than oxidizer, which suggests that the impact of heat feedback of Aluminum particle combustion to heat balance of the burning surface could not be ignored.

4. Conclusion

Concluding the above discussion, we may state the following:

(1) In the first stage of combustion, there would be diffusion flame, while in the final stage the flame would transform into premixed flame. No dark zone exists in the flame but a molten layer exists during the whole combustion process.

(2) With backpressure increasing, the burning rate would increase with a reduced increasing range. For no-Aluminum-contained NEPE propellant, increasing backpressure would cause a more homogeneous and brighter flame and a more obvious diffusion flame structure. For Aluminum-contained NEPE propellant, increasing backpressure would cause severer reactions in the reaction zone and a more homogeneous and brighter flame.

(3) The grain size of oxidizer would have more impact on burning rate than Aluminum. For oxidizer, the grain size of AP would have more impact on burning rate than HMX.

(4) The grain size of Aluminum would have more impact on burning rate pressure exponent than oxidizer. For oxidizer, the grain size of AP has more impact on burning rate pressure exponent than HMX.

(5) The grain sizes of AP and HMX might have little impact on flame structure. There would be diffusion flame in the first stage and premixed flame in the final stage. For no-Aluminum-contained NEPE propellant, the reaction in the gas phase might be dominant in the combustion. For Aluminum-contained NEPE propellant, the reaction in the solid phase would be dominant in the final stage since Aluminum particles would react both on the burning surface and in the gas phase reaction zone.

(6) Through analyzing the burning surface temperature and the flame structure of four kinds of NEPE propellant, it could be found that after the addition of Aluminum particles with small grain size, the zone in which the combustion of Aluminum particles happened would be closer to the burning surface and the burning surface temperature would increase obviously. It could be suggested that the heat feedback of combustion of Aluminum particles to burning surface might not be ignored.

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