

Article

A Study on Combustion Characteristics of Insensitive Triple-Base Propellant

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Abstract: Research on combustion characteristics can provide basic information and theoretical support for the design of insensitive propellant. This work aims to investigate the combustion characteristics of insensitive triple-base propellant. All propellants were prepared based on same triple-base propellant, but they were desensitized with the same desensitizer in different ways. The high-speed camera, spontaneous luminescence, NO, NH chemiluminescence, and OH-planar laser induction fluorescence (PLIF) methods were employed to capture the combustion flame and derive the distributions of important intermediates. Results show that ignition delay times of insensitive propellants are obviously longer. This indicated that the application of the desensitizer has a partly hindering effect on the early ignition stage. The combustion time of insensitive propellants is mostly similar, which means that the desensitizer has little influence on the intensity of actual combustion. The change in flame height and area of insensitive propellants over time indicated that the combustion progressivity of some insensitive propellants was more prominent, which means that the desensitizer concentration and desensitizing methods all affect the performance of insensitive propellant. The signal intensities of NO and NH show a negative correlation, indicating that a competitive relationship probably exists between the formation of NO and NH radicals during the reaction process. The high concentration of OH mainly locates outside NO, suggesting that there may be a transformation between NO and OH. The maximum signal intensity of NO and NH of different insensitive propellants confirmed that both the concentration of desensitizers and the desensitizing methods exhibit important effect on the reaction process.

Keywords: combustion; insensitive propellant; optical diagnosis; NO chemiluminescence; NH chemiluminescence



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1. Introduction

Triple-base propellant is a kind of high-energy propellant, and it has been widely used in the field of artillery propulsion [1]. Specifically, gun bore erosion has become an important factor limiting the power and life of artillery [2]. The insensitive triple-base propellant can effectively reduce erosion and prolong gun barrel life.

In recent years, research on insensitive propellants has been conducted step by step. At present, most related research was carried out to develop new desensitizer components and desensitizing methods, as well as to learn the macro combustion characteristics of the insensitive propellant. Elbasuney et al. [3] accomplished the consideration of an ammonium perchlorate/cyclo-trimethylene-trinitramine (AP/RDX) co-crystal, with superior thermal behavior and an increase in RDX decomposition enthalpy. Wu et al. [4] prepared NTO/HMX-based PBX through the water suspension method. It was found that, after refining particle size, the impact sensitivity is decreased, and the maximum detonation velocity is above 95% of the theoretical one. Yan et al. [5] prepared a new insensitive and high energy explosive, based on RDX (e-RDX), by suspension spray technology, using

Estane 5703 as a binder, and the activation energy of e-RDX was lower than that of raw RDX. The energetic materials, which have been desensitized by different materials and methods, show certain superiority in performance. Additionally, the physicochemical properties of desensitizers were studied. Louden et al. [6] used Raman spectroscopy to explore the distribution of desensitizers in a small-size single-base propellant. Yao et al. [7] prepared CL-20/RDX and characterized thermal decomposition property, explosion performance, and mechanical sensitivity of different kinds of micron-sized spherical CL-20/RDX, such as critical temperature of thermal explosion. These studies focused on the production process, application effect, and physical and chemical properties of desensitizers, as well as the macroscopic properties of combustion, such as the burning rates and the pressure exponent of burning rates and detonation propagation [8–10]. However, the microscopic combustion process and combustion mechanism of insensitive propellant are still not clear at present, while this information can provide important information, as well as theoretical and technical support, for the design and use of insensitive propellant.

For the microscopic reaction mechanism research of energetic materials, the main research methodologies are thermal decomposition experiments and numerical simulations. These two methods have been extensively adopted in previous works. Manhas et al. [11] determined the thermochemical properties and decomposition characteristics using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Chen et al. [12] found the effects of Sn-containing intermetallic compounds on the thermal decomposition and ignition properties of RDX and TKX-50 through thermal-decomposing tests and high-power laser ignition. Liao et al. [13] numerically analyzed the spontaneous combustion process of RDX. Gas chromatography-mass spectrometry (GC/MS) and Fourier transform infrared spectroscopy (FTIR) were used for the detection of several components produced in the combustion of energetic materials. Cropek et al. [14] used GC/MS to analyze the pyrolysis products of the double-base propellant composed of nitrocotton and nitroglycerin. Chen et al. [15] utilized TG-DSC-IR-GC-MS technology to study the decomposition of a novel nitrated bacterial cellulose/cyclotrimethylenetrinitramine (NBC/RDX) nanocomposite energetic material. Zhang et al. [16] studied the interaction mechanism of 1H-tetrazole and nitrocellulose by kinetics methods and TG-DSC-FTIR analysis. Kim et al. [17] used FTIR to study the combustion gas products of standard rocket propellant and actual rocket propellant. To know the flame structure of energetic materials, the methods of probe mass spectrometry, micro thermocouple technology, and spectroscopy are always utilized. Spectroscopic methods include Planar Laser Induced Fluorescence (PLIF), Spontaneous Raman Scattering (SRS), and Coherent Anti-Stokes Raman Scattering (CARS). Among them, PLIF technology has the advantages of high sensitivity, as well as high spatial and temporal resolution. It is considered to be well suited for diagnosing flame structure and understanding combustion processes. Parr et al. [18] studied the deflagration process of HNF, RDX, HMX, and XM39 by PLIF, ultraviolet/visible absorption, and thermocouple methods. Ruesch et al. [19] used PLIF technology to study the distributions of CN and OH of cocrystals of CL-20 and a polycrystalline composite crystal of HMX/AP.

However, as innovation of energetic materials continues, propellants are becoming more and more diverse in their composition and more complex in their combustion reactions, particularly with triple-base propellant. Until now, triple-base propellant has not been well understood by investigating the chemical reaction process from the micro-perspective. Therefore, in this study, self-luminescence, NO, and NH chemiluminescence, as well as OH-PLIF, were adopted to carry out an in-depth analysis on the combustion of insensitive tri-base propellant. The distribution patterns of NO, NH, and OH free radicals were obtained, which can characterize the microscale flame structure to a certain extent, help to identify the dominant factors in combustion, and also help modelers to create dynamic and flame structure models of triple-base propellants. Additionally, evaluating the combustion behaviors of some insensitive propellant from a microscopic perspective was expected to guide the design and use of insensitive propellant.

2. Materials and Methods

The energetic materials used in the experiment were five kinds of triple-base propellants. The basic formulations of the five propellants were identical. The main component is a mixture of nitrocotton (NC), nitroglycerin (NG), nitroguanidine (NQ), and energetic plasticizer diazidonitrazapentane (DIANP). The mixture ratio of the formulations of five propellants was the same. Except for the blank propellant, the other four propellants were desensitized with a kind of desensitizer, but in different ways. In this paper, the five propellants were named 1#, 2#, 3#, 4#, and 5#, according to their different desensitizing methods and desensitizer contents. The content of the desensitizer was 0%, 1%, 1.2%, 1.5%, and 1.2%, respectively. They were provided by Xi'an Modern Chemistry Institute. The appearance of the propellant was composed of white, solid large particles. The particle size was maintained at the millimeter level, with slight differences between different propellants. The structure was polyhedral in shape, with relatively smooth surface cutting and sharp corners, as well as some pits and bumps. Except for the blank propellant, the other four propellants were desensitized in the same desensitizer, but in different ways.

The experimental system shown in Figure 1 contains four main parts: sample platform, laser diagnosis, chemiluminescence platform, and data acquisition platform.

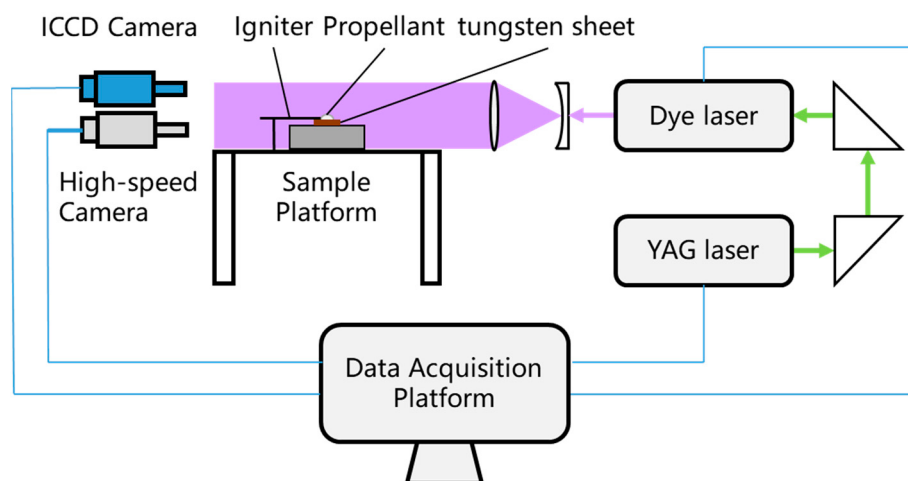


Figure 1. Setup of the experimental system.

The sample platform was used to hold and ignite the propellant. The sample was placed on the tungsten sheet and made a round cake with a diameter of 10 mm and a thickness of 2 ± 0.1 mm, and the sample mass was kept at 200 ± 0.1 mg. Then, the tungsten sheet was placed on the object stage. The sample was ignited with the electronic pulse ignition method. Then, the propellant burned in self-propagation. The whole ignition and combustion processes were captured with a high-speed camera. The species of NO, OH, and NH were diagnosed with PLIF and chemiluminescence methods.

The OH-PLIF laser platforms mainly involved the Nd:YAG laser, the dye laser, and the lens group. As an excellent laser diagnosis method, OH-PLIF was widely used in the combustion of gas, liquid, and solid fuels [20–22]. By generating a certain wavelength of laser light, the OH radical in the flame could be induced to produce fluorescence, and the two-dimensional concentration distribution of free radicals in the flame could be measured. NO/NH chemiluminescence did not require a laser platform, and an ICCD camera was employed to shoot.

The OH-PLIF laser diagnostic platform used a 10 Hz Nd: YAG laser to output 566.046 nm pump laser after double frequency, and then it generated light with a wavelength of 283.023 nm and energy of 16 mJ after passing through the dye laser. Then, the light entered the lens group to generate a light sheet and passed through the sample center to excite the OH radicals during the reaction.

Finally, the data acquisition platform mainly included a computer, a high-speed camera (Ametek, Wayne, NJ, USA, Phantom V611), and an ICCD camera (LaVision GmbH, Göttingen, Germany, LaVision Image Prox 2M). This platform was started and kept taking pictures to capture the whole combustion process.

The experiment was carried out under normal temperature, pressure, and air environment. The detailed information of the experiments for diagnosing different species is as follows.

(1) In the spontaneous light acquisition of combustion flame, a computer combining a high-speed camera were used to record the reaction and combustion process of the propellant. The resolution of the high-speed camera was 800×600 , the shooting rate was 600 fps, and the exposure time was 1600 s.

(2) In the NO chemiluminescence experiment, the computer, combined with the ICCD camera, recorded the chemiluminescence signals of NO free radicals during the combustion of the propellant. A NO filter (FWHM:10 nm), with a central wavelength of 248 nm, was installed in front of the ICCD lens. The gate width was 200 s. The gain was 60%, and the maximum camera frequency was 4 Hz.

(3) In the NH chemiluminescence experiment, the computer, combined with the ICCD camera, recorded the chemiluminescence signals of NH free radicals during the combustion of the propellant. Similarly, a NH filter (FWHM:10 nm), with a central wavelength of 337 nm, was installed in front of the ICCD lens. The gate width was 200 s. The gain was 60%, and the maximum camera frequency was 4 Hz.

(4) In the OH-PLIF experiment, a computer, combined with the ICCD and OH-PLIF laser diagnostic platform, were used. A 308 nm OH filter (FWHM:10 nm) was installed in front of the ICCD lens. The delay of the ICCD camera was 100 ns, the gate width was 200 ns, and the gain was 60%. The frequency synchronization between the laser and the ICCD was 3.87 Hz.

Due to the different frequencies of the equipment, the results of these four kinds of measurements above were slightly different in time. However, this would not affect the understanding and research of the reaction process. To ensure the repeatability of the experiment, each measurement was repeated three times.

3. Results and Discussion

3.1. Self-Illuminating Properties of the Combustion Flame

With the high-speed camera, the whole ignition and combustion processes were recorded. Figure 2 showed the flame self-illumination image during the ignition delay period, with 2# propellant as an example. The ignition delay time was one of the important parameters to describe the ignition process. There were various definitions for the ignition delay time. Considering the ignition method employed in the present study, the ignition delay time was defined as the period from the moment when the electronic pulse was started to the moment when the initial flame appeared obvious, and the flame area was about 10 mm^2 . The initiation time of the pulse igniter was denoted as 0 s. The self-luminous image of the combustion reaction of 200 mg propellant can be obtained by continuous shooting with the high-speed camera. By analyzing the images taken by the high-speed camera, the ignition delay time and combustion time of the same propellant were derived as the average value of repeated experiments.

To further understand the ignition and combustion process of the insensitive propellant, the present study took the 2# insensitive propellant as an example and defined the ignition time of the pulse igniter as 0 s. The combustion process of the 2# insensitive propellant was shown in Figure 3. The whole combustion process could be divided into a flame development period (0~0.9 s), a stable burning period (1.0~2.2 s), and a flame decline period (2.3~2.9 s). After the propellant was ignited, it rapidly developed upward in a short time. The burning intensity gradually increased, the flame brightness enhanced, and, then, most of the particles started to burn, entering the stable burning period. As time went by, the flame gradually entered the decline period. The flame height and area decreased. The

flame brightness also gradually declined, and it finally completely disappeared. It is obviously seen that the flame development time was longer than the decline period. This might be because the overall energy density was reduced after the addition of the desensitizer, and the burning rate hence decreased. Additionally, the composition of desensitizer had an obstructive effect on flame combustion in the development period.

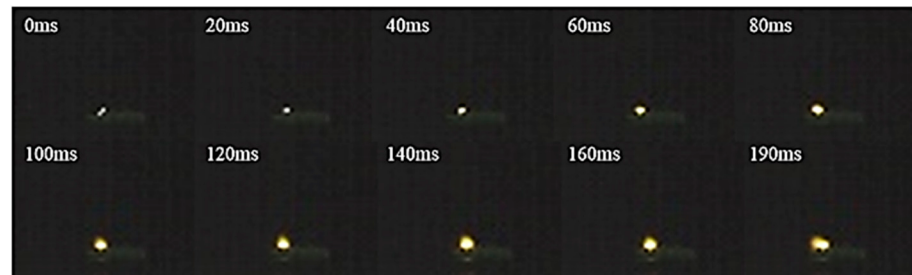


Figure 2. The ignition process of the 2# insensitive propellant.

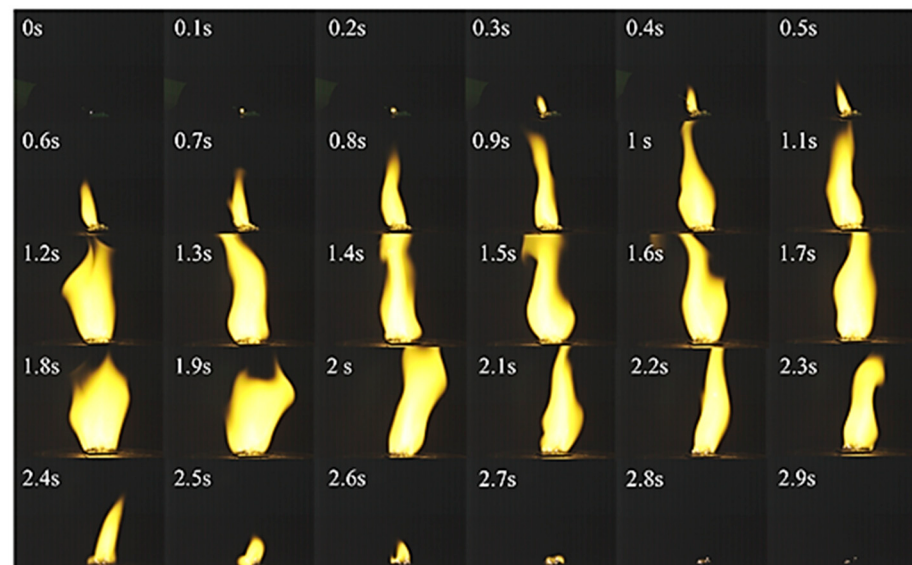


Figure 3. The combustion process of the 2# insensitive propellant.

Figure 4 shows the ignition delay time and combustion time of different propellants. It can be seen that, compared to the blank propellant, the ignition delay times of four insensitive propellants were obviously greater. This indicated the application of desensitizer had a partly hindering effect on the early ignition stage, and the insensitive propellants needed higher ignition energy and longer ignition time. The ignition delay period reflects the desensitizing effect of energetic materials to a certain extent. With longer ignition delay period, the thermal response of energetic materials is slower, and the thermal stability is better, and the effect of the desensitizer is more obvious. Specifically, the ignition delay time of 2# was the longest, and that of 4# was the shortest among the four insensitive propellants. Among these four groups of samples, there was no clear correlation between the content of desensitizer and ignition delay time. It should be noted that 2# had the lowest desensitizer content of 1%, while 4# had the highest desensitizer content of 1.5%. This indicated that the ignition process could be affected by both desensitizer content, as well as the desensitization method, and the effect of the desensitization method could be more significant.

Regarding the combustion process, the combustion time of insensitive propellants was mostly similar to that of blank propellant, which means the desensitizer had little influence on the intensity of actual combustion. Thus, it was concluded that the performance of the

propellant was limitedly affected by adding an amount of desensitizer. Specifically, among the insensitive propellants, the burning time of 2# was the longest, just as the ignition delay time. This indicates the desensitizer could both affect the ignition and combustion processes. The burning times of 3# and 5# were even slightly shorter than that of 1# propellant, though these two propellants were desensitized with 1.2% desensitizer. The combustion time of 3# propellant was relatively shorter, and the combustion intensity was slightly greater than others. Therefore, the different desensitization methods had a certain effect on the combustion time, and they even shortened the combustion time.

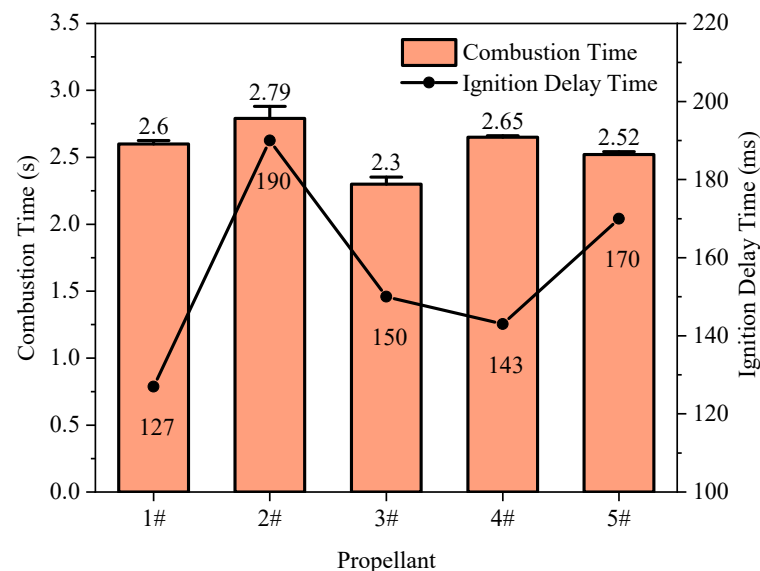


Figure 4. The ignition delay time and combustion time of different propellants.

In the experiments, all five propellants burned in the way of self-propagation after ignition, so the change rate of the flame height could characterize the flame propagation rate and reflect the combustion behavior of the five propellants to some extent. The flame area reflected the consumption rate of propellant in the combustion process, and it also reflected the intensity of early combustion.

Figure 5 displayed the change in flame height of five propellants over time. It could be seen that, compared with the blank propellant, 3# almost exhibited similar behavior. Additionally, 4# had slightly higher value at the early stage while almost having the same value after the early stage. The propellants of 2# and 5# had lower flame height at all combustion processes, especially in the early stage, demonstrating that their ignition process was inhibited. This was consistent with their longer ignition delay period discussed above. Figure 6 demonstrated the change in flame area with time for the five propellants. It was seen that the curves of 3# and 4# were very close with that of the 1# blank propellants, while the values of 2# and 5# were relatively lower. This showed that these two desensitizing methods for 2# and 5# had a great influence on the intensity of early combustion of the propellant. Figure 7 showed the change rate of the flame height of five propellants between 0–1 s. It could be seen that the values of five propellants increased with time, indicating the combustion progressivity of these propellants. In practical application, the energy of the progressive combustion propellant gradually releases, which is conducive to form a pressure platform near the maximum pressure, improve ballistic performance, and thus enhance the firing rate of the gun. The maximum flame height change rates of 2# and 5# were higher than that of 1# propellant, so the combustion progressivity was more prominent. Therefore, the ballistic performance of these two propellants may be better. The fluctuation phenomenon of flame height variation rate might be caused by the uneven heating of the gas above the flame, which tended to appear as turbulent flow. At the same time, the intensity of combustion increased, resulting in the deterioration of flame stability.

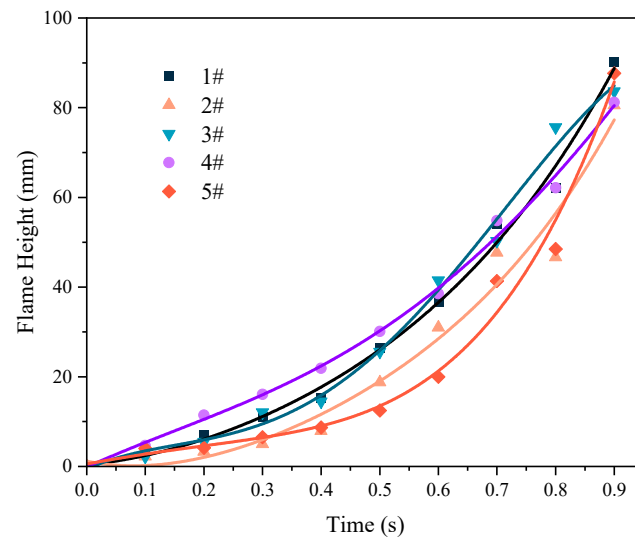


Figure 5. Flame height of the propellants over time.

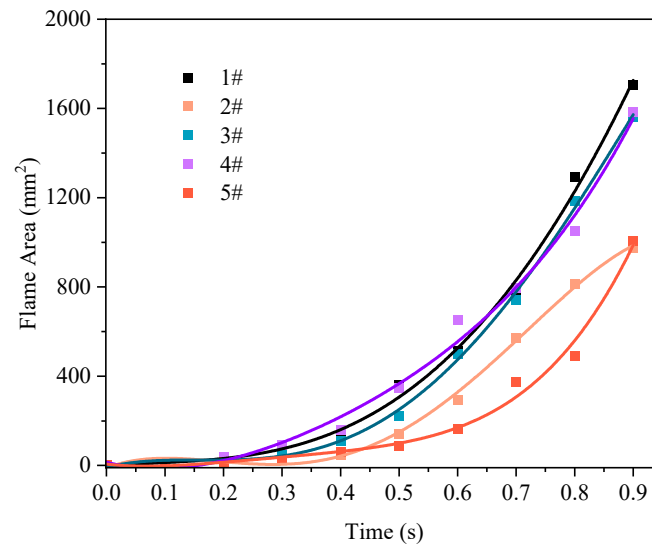


Figure 6. Flame area of the propellants over time.

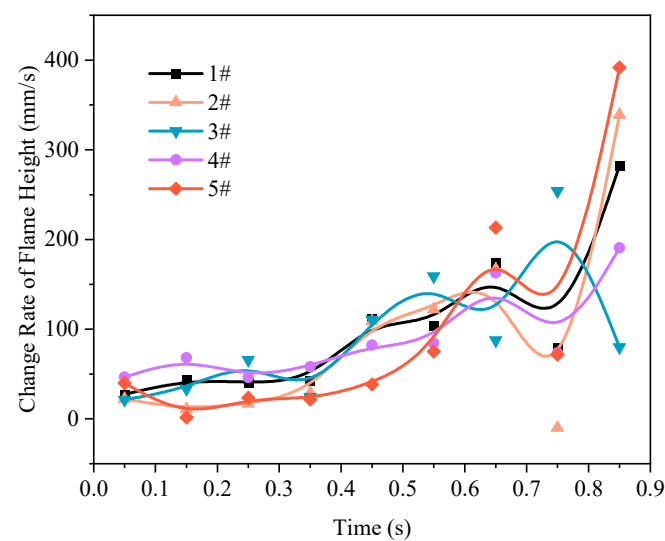


Figure 7. Change rate of flame height for five propellants over time.

3.2. NO and NH Chemiluminescence Characteristics

The gas-phase products near the combustion surface of propellants can be divided into five main categories: NO_2 , CH_2O , CHO , CH , and CO . They represent oxidant, reducing agent, crackable radical, and the two neutral radicals in sequence [23]. During the reaction process, complex macromolecular propellants decomposed and oxidized continuously, producing gas-phase intermediates, such as NO_2 , which could be consumed through the following reactions, and free radicals such as OH and NO would be produced in the whole process.

Chemiluminescence refers to the phenomenon that free radicals excited by chemical reactions produce light radiation during their return from the excited state to the ground state. Consequently, information about the flame structure and flame process can be identified through chemiluminescence. Since most energetic materials are nitrogenous substances, the chemiluminescence of NO and NH radicals in energetic materials can provide reliable information and important reference for understanding the combustion reaction process.

The moment when the NO signal appeared was defined as the beginning. Figure 8 showed that the distribution of NO chemiluminescence signals in the flame varied with time for different propellants. It can be seen that the overall signal intensity showed a trend of first increasing and then decreasing. The NO signal appeared inside the flame, but the main signal was concentrated in the upstream and midstream wings of the flame. It was speculated that the appearance of the NO signal might originate from two different transformation processes.

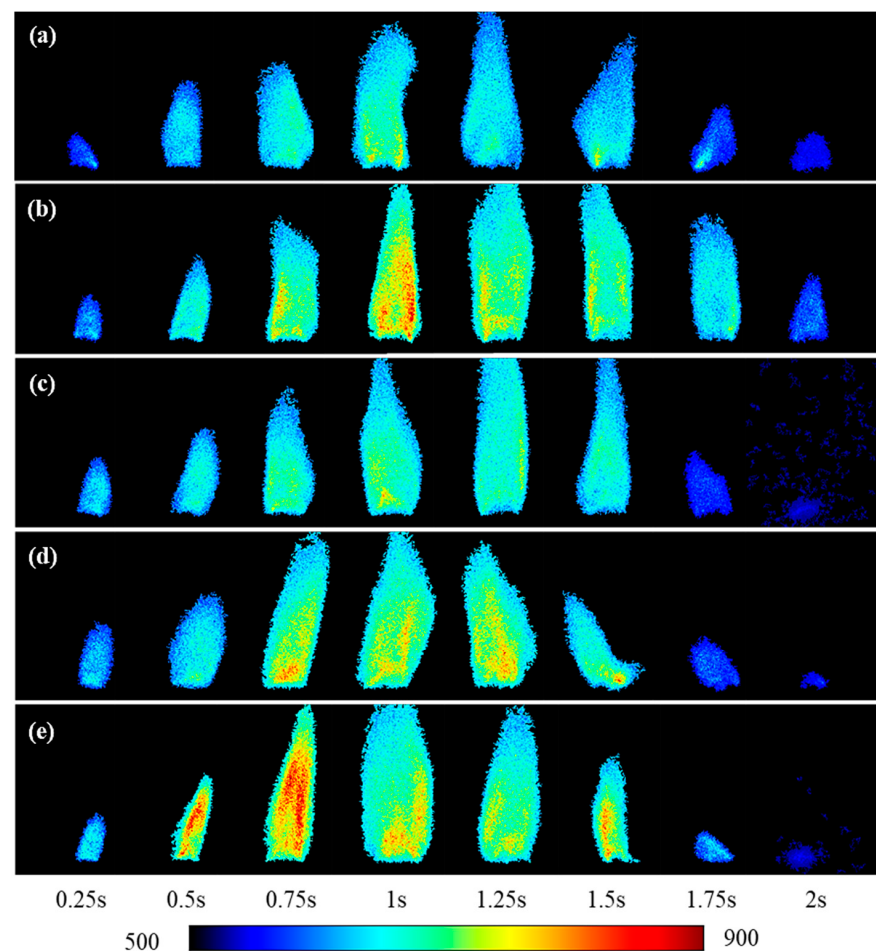


Figure 8. NO chemiluminescence signal distribution. (a) 1#; (b) 2#; (c) 3#; (d) 4#; (e) 5#.

The appearance of NO at the bottom may be derived from the conversion of the intermediate NO_2 . NO_2 was an important intermediate product in the pyrolysis of triple-base propellant. The dissociation energy of N- NO_2 and O- NO_2 bonds in the propellant was very low, so NO_2 can appear at early low temperatures [24]. After NO_2 was produced, it trapped protons to form HONO, in which the -OHO bond breaks to form NO [25]. Additionally, the appearance of NO involved the decomposition of solid-phase products, including the NO_2 -catalyzed decomposition of nitrate ester [26–28], which accelerated the breaking of N- NO_2 and O- NO_2 bonds. As seen in Figure 8, the appearance of NO in the two wings might be caused by the reaction with the intermediate gas-phase products, including CH_2O and CO. With the increase in flame height, the NO signal was further weakened, and the unstable NO was converted into stable reaction products, including N_2 , H_2O , etc.

The NO signal map captured by LaVision was extracted to obtain the change in the maximum signal intensity of NO in the flame over time, as shown in Figure 9. It can be seen that the maximum signal intensity of NO increased with the development of flame and decreased with the decline of flame, and the maximum NO signal appeared in the stable burning period. By comparing the maximum NO signals of five propellants, it was found that the maximum signal intensity of the four insensitive propellants was higher than that of the blank one. This indicated that the concentration of NO generated by the insensitive propellants were higher in the actual combustion process.

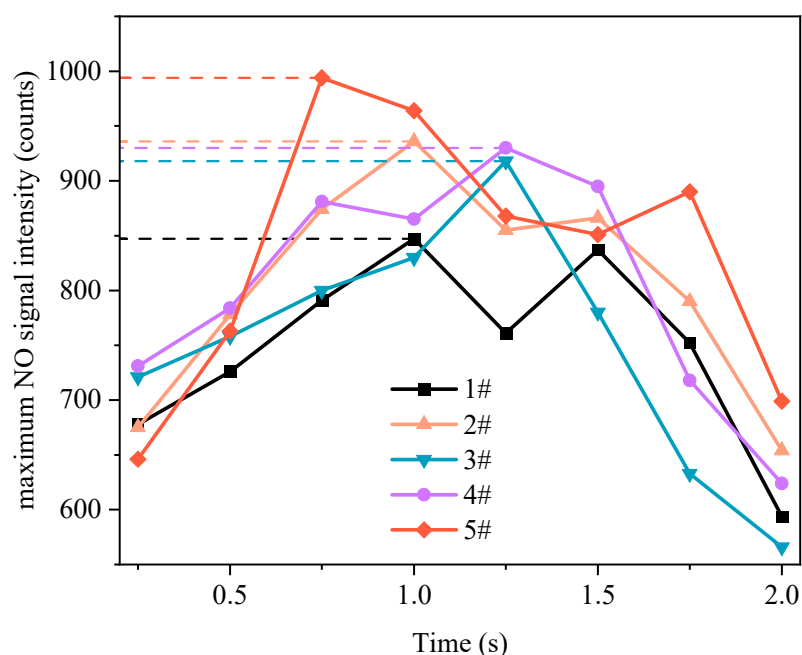


Figure 9. Maximum signal intensity of NO in the flame over time.

Regarding NH signal, the moment of NH signal appearance was defined as the beginning. Figure 10 showed the distribution of NH chemiluminescence signals with time for different propellant flames. It could be seen that, similar to the NO signal, the overall NH signal presented a trend of first strengthening and then weakening. The stronger NH signal, i.e., the higher NH radical concentration, was mainly found in the upper part of the flame. It can be clearly observed that the NH signal of blank propellant was strong, and the high concentration of NH was distributed in the whole flame center, while the concentration of NH of insensitive propellants was significantly lower. In the upstream region of the flame, the initial decomposition of the propellant macromolecules took place. In the upstream region of the flame, the initial decomposition of the propellant macromolecules took place, which was associated with the production of NH radicals. By researching multi-base propellants, it was speculated that the generation of NH was highly related to the decomposition of NQ, which produced the intermediate product of NH_3 .

soon after being heated [29], then NH_3 might form the NH radical by constantly capturing the OH radical, free O , or free H during the reaction process [30–32]. The reaction between NH_3 and NO_2 would also produce the NH radical [33].

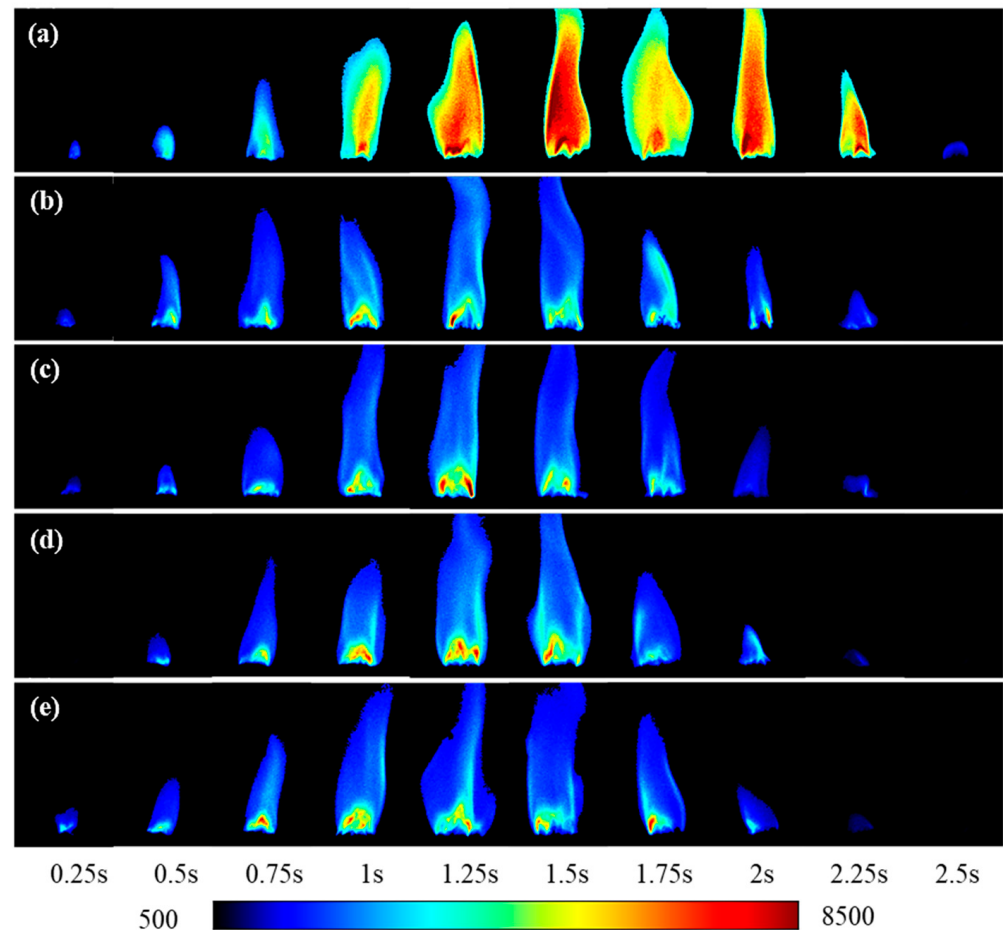


Figure 10. NH chemiluminescence signal distribution. (a) 1#; (b) 2#; (c) 3#; (d) 4#; (e) 5#.

The NH signal captured by LaVision system was extracted to obtain the change in maximum signal intensity of NH in flame over time, as shown in Figure 11. It can be seen from the figure that the maximum signal intensity of NH exhibited similar behavior with the flame development process that it increased with the development of flame and decreased with the decline of flame, and the maximum signal of NH mainly appeared in the stable burning period. By comparing the maximum NH signals of the five propellants, it was found that the maximum signal intensity of the four insensitive propellants was lower than that of the blank propellant, and the signal intensity of 2# was the lowest. This indicated that, in the actual combustion process, the insensitive propellant produced a lower concentration of NH during combustion. The desensitizer effect was affected not only by the concentration of desensitizers but the desensitizing methods. Since NH was derived from NH_3 , which was obtained from the decomposition of NQ , the decrease in the concentration of NH indicated that the process of NH_3 produced from the decomposition of NQ might be inhibited to some extent in the combustion process of insensitive propellant. Meanwhile, compared with the signal intensity of NO in the previous figure, it was found that the signal intensities of NO and NH showed a negative correlation, indicating that there might be a competitive relationship between the formation of NO and NH radicals in the reaction process.

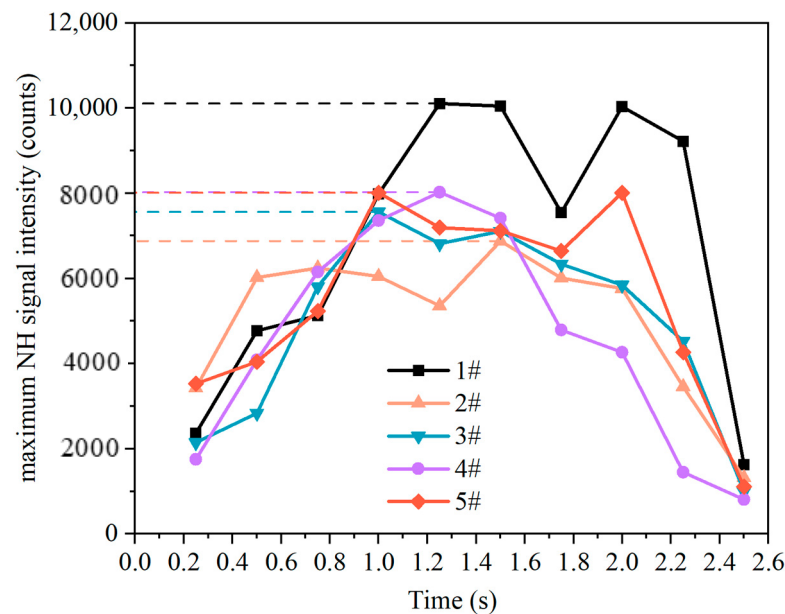


Figure 11. Maximum signal intensity of NH in the flame over time.

3.3. OH-PLIF Signal of Propellants

The OH radical was an important intermediate product in the combustion process, characterizing the flame structure and reflecting the flame combustion intensity. In this study, the OH signal during combustion was measured by OH-PLIF laser diagnostic platform. The moment of the appearance of the NO signal was defined as the beginning. As can be seen from Figure 12, an OH radical was generated along with the flame, and the signal intensity increased first and then decreased. Additionally, an OH signal was mainly located in two wings of the middle parts and the downstream of the flame, namely, the peripheral part of the flame. The high concentration area was mainly located in two wings of the middle part, which was outside the NO signal, indicating that there might be a transformation between NO and OH [34]. Yetter et al. [35] pointed out several paths of conversion between NO and OH, including reactions between NO with H radical, NH_2 radical, and H_2O . Similarly, there might also be some conversions between the NH radical and the OH radical [36].

The OH-PLIF signal map, captured by LaVision, was extracted to compare the changes in maximum signal intensity of OH in different flames over time, as shown in Figure 13. It could be seen that the maximum signal intensity of OH increased with the development of flame and decreased with the decline of flame, just as with the flame development process. The time when the maximum OH signal appeared was unstable, but it still appeared in the stable combustion period. By comparing the maximum OH signals of the five propellants, it was found that the maximum signal intensities of the four insensitive propellants were higher than that of the blank one, among which the signal intensity of 3# was the highest. This indicated that the concentration of OH produced by 3# was relatively higher in the actual combustion process, and the intensity of the oxidation reaction was relatively stronger. However, the overall concentration of OH was approximate, so it could be concluded that, in the actual combustion process, the desensitizer would not affect the combustion intensity of the propellant and even enhance the combustion process.

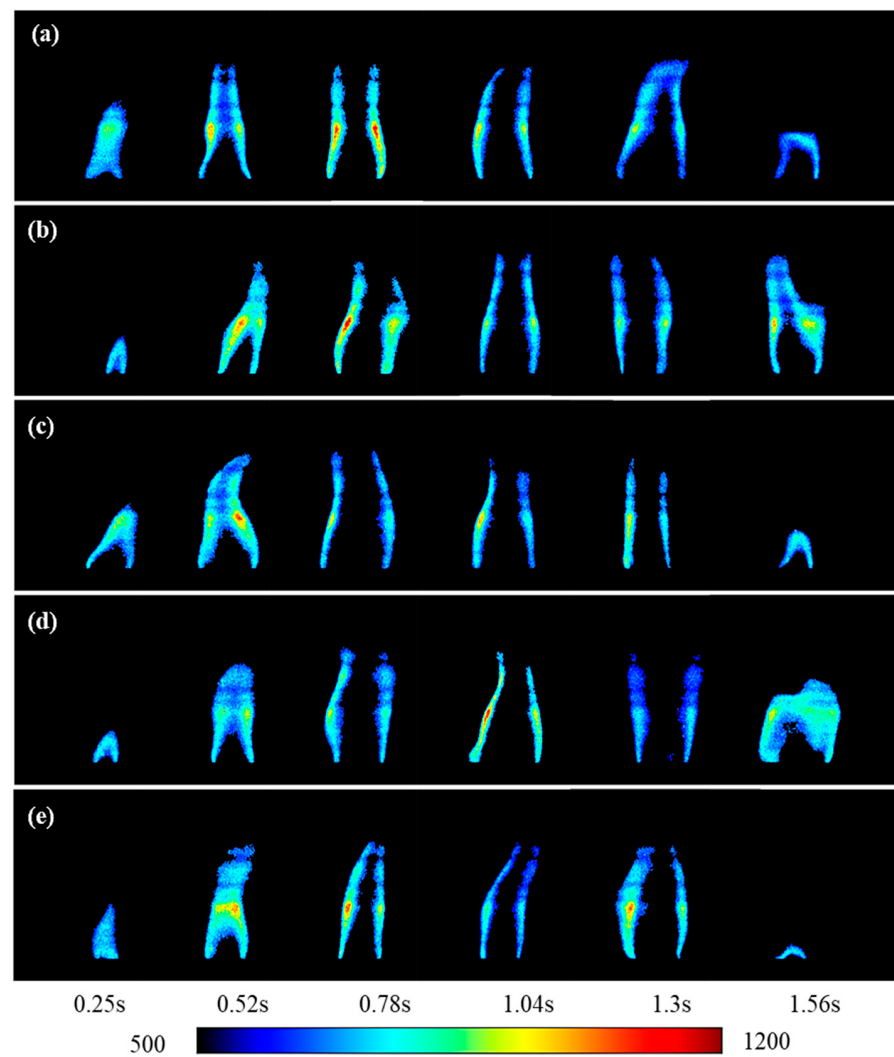


Figure 12. OH-PLIF signal distribution. (a) 1#; (b) 2#; (c) 3#; (d) 4#; (e) 5#.

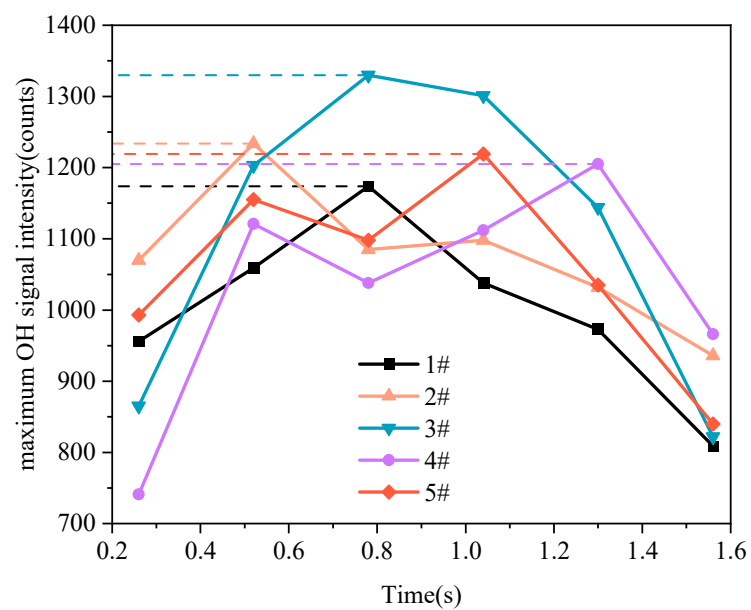


Figure 13. Maximum signal intensity of OH in the flame over time.

4. Conclusions

In this paper, spontaneous luminescence, NO, NH chemiluminescence, and OH-PLIF methods were used to investigate the combustion phenomena of five triple-base propellants. The combustion performance of different propellants was comparatively evaluated. The main conclusions are as follows.

(1) The insensitive propellant needs higher ignition energy and longer ignition time, and the duration of flame development is longer than that of decline, which means the desensitizer has an obstructive effect on flame propagation in the early ignition stage and the development period. However, the combustion time of insensitive propellants are mostly similar, showing the desensitizer has little influence on the intensity of whole combustion.

(2) The intensity of early combustion of some insensitive propellants are lower, but higher in late stage of development, which means the combustion progressivity are more prominent. In the actual process of desensitizer, the desensitizer concentration and desensitizing methods all affect the performance of the insensitive propellant.

(3) The NO signal concentrates are in the interior of the flame. The OH signal locates in outer part of the flame, indicating that there might be transformation between NO/NH and OH. The NH radical mainly appears upstream of the flame. Additionally, there might be a competitive relationship between the formation of NO and NH radicals during the reaction.

(4) The maximum signal intensity of NO and NH are different for the five propellants, demonstrating that the desensitizer effect is affected not only by the concentration of desensitizers, but also by the desensitizing methods. It is interesting that the signal of NH in insensitive propellants is significantly lower than blank one. Future mechanism research should focus these initial findings of the formation and change in NH radical in the reaction process of insensitive propellant.

The investigation of the complete combustion process, as well as the distribution and concentrations of NO, NH, and OH radicals, can characterize the microscale flame structure to a certain extent, help to identify the dominant factors in combustion, and also help modelers to create dynamic and flame structure models. However, the composition of the tri-base propellant is complex, so further kinetic work is necessary to learn the detailed chemical reaction process and the influence factors.

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