

OXIDIZER AND GAS-ENVIRONMENT EFFECTS ON AFTERBURNING REACTIONS AND EXPLOSION PERFORMANCES OF HMX-BASED THERMOBARIC EXPLOSIVES

OKOLJSKI VPLIVI OKSIDANTOV IN PLINOV NA POZGOREVALNE REAKCIJE IN EKSPLOZIJSKE LASTNOSTI TERMOBARIČNIH EKSPLOZIVOV NA OSNOVI HMX

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In this paper, confined explosions of HMX-based thermobaric explosives containing oxidizers in a spherical chamber were studied by changing the type of the oxidizer and the oxygen concentration in the environment. Based on an in-house developed optical-electrical system, the optical radiation signals of Al_2O_3 during the afterburning reaction were recorded. The results show that aluminum particles ($5.4 \mu\text{m}$) were strongly dependent on the oxygen concentration in the environment. Increasing the oxygen concentration can prolong the oxidation duration of Al and enhance the optical radiation intensity of Al_2O_3 . The optical radiation result for Al_2O_3 in O_2 and air showed that aluminum particles (the mass fraction was 33 %) were not completely oxidized in the air, and the oxidation duration was 500–700 μs . Moreover, the pressure data of the blast waves was obtained using a pressure-measurement system. The results showed that an increase in the oxygen concentration of the explosive could further enhance the total impulse, especially an addition of KP (its mass fraction was 10 %) could increase the total impulse by about 9 %.

Keywords: thermobaric explosive, afterburning reaction, optical radiation, oxidizer

Avtorji v članku opisujejo študijo vpliva spremembe vrste oksidanta in koncentracije kisika v okolju. Gre za v zaprti komori omejene eksplozije termobaričnih eksplozivov na osnovi HMX, ki vsebujejo različne oksidante. S pomočjo doma razvitega optično-električnega sistema so lahko avtorji zasledovali signale sevanja Al_2O_3 med pozgorevalnimi reakcijami. Rezultati preizkusov so pokazali, da je obnašanje aluminijastih (Al) delcev povprečne velikosti $5,4 \mu\text{m}$ močno odvisno od koncentracije kisika v okolici. Naraščajoča koncentracija kisika v okolici eksplozije lahko podaljša trajanje oksidacije Al in izboljša intenziteto optičnega sevanja Al_2O_3 . Rezultati meritve optičnega sevanja Al_2O_3 v kisiku in zraku kažejo, da Al delci, katerih masni delež je bil 33 %, niso bili popolnoma oksidirani v zraku in da je oksidacija trajala od 500 μs do 700 μs . Avtorji so izvajali meritve tlaka udarnih valov s pomočjo posebnega tlačnega merilnega sistema. Rezultati so pokazali, da povečanje koncentracije kisika v eksplozivu lahko poveča celoten impulz. Ta se znatno poveča (za cca 9 %), če eksplozivu dodamo 10 w/% kalijevega perklorata (KP).

Gljučne besede: termobarični eksploziv, pozgorevalne reakcije, optično sevanje, oksidanti

1 INTRODUCTION

Currently, the significant pressure and thermal effect of a thermobaric explosive is the focus of research. Some researchers reviewed the composition, heterogeneous explosion, explosion characteristics and the method for determining the explosion parameters of thermobaric explosives.^{1,2} Aluminum as the preferred metal fuel is always added to thermobaric explosives because of its advantages including high combustion heat and easy availability. However, the energy gain of fuel-rich thermobaric explosives did not meet the expectations due to incomplete combustion of aluminum particles.³ During the explosion, the oxidation of aluminum particles was complex and went through multiple stages.⁴

In this regard, many scholars made an in-depth research on the ignition mechanism and burning process of aluminum particles. T. A. Brzustowski et al.⁵ speculated that particle ignition would not occur until the oxide shell melted at its melting point and the subsequent combustion would reach a steady state with aluminum at its boiling point. V. M. Boiko et al.⁶ observed the ignition of several metals and found that the particles would ignite due to a rupture of the oxide shell caused by mechanical stress. M. F. Gogulya et al.⁷ obtained the temperature data for the explosive products at the front of the explosion. The results showed that the active surface of Al particles determined the initial stage of metal oxidation. S. D. Gilev et al.⁸ maintained that the reaction of aluminum with detonation products was carried out on the thin surface layer of the particles, forming stable chemical compounds. The formed layer prevented oxygen from entering the interior of the particles.

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One of the effective methods of improving the burning rate of aluminum powder is to change its content and particle size. Previous studies^{4,9,10} showed that the surface reaction kinetics limited the combustion of aluminum powder with a particle size less than 20 μm . Based on the results of explosion tests, J. E. Monat et al.¹¹ found that the complexity of particle reaction kinetics had suppressed the advantages of high-energy metal fuel. W. A. Trzciński et al.¹² confirmed that aluminum particles with a high specific surface area are conducive to the heat exchange and oxidation of aluminum, detonation products and air. The extra heat released by the fine aluminum powder's oxidation reactions increased the temperature of the explosive products, thereby increasing the chamber's pressure. K. L. McNesby et al.¹³ found that the combustion reaction of aluminum particles with a smaller size stopped faster than that of large particles. The reason for this may be the fact that smaller aluminum particles are not pushed into the mixture layer (an oxygen-rich gas environment) of reactants by the blast wave, while large aluminum particles are more likely to be pushed into it, in which case, a stronger afterburning reaction may be caused.

Because of the detonation products and other additives, the oxidation reaction of aluminum particles became more complicated. The concentration of gaseous substances, such as oxygen, affected the afterburning reaction. According to the result of some studies^{11,14}, the aluminum particles of the thermobaric explosive were combusted incompletely, and more than 62.0 % of O of Al_2O_3 came from the air. The test results of R. J. Gill et al.⁴ showed that the burning time of aluminum particles would increase when the concentration of oxygen was reduced. In an oxygen-rich environment (oxygen concentration exceeding 21 %), the effect of oxygen concentration on the burning time of micron-sized aluminum particles was slight. In such a case, high-energy oxidizers were added to thermobaric explosives to oxidize more massive amounts of aluminum particles.

AP (ammonium perchlorate) and KP (potassium perchlorate) contribute more O through a thermal decomposition reaction. M. A. Cooper et al.¹⁵ showed that AP improved the oxygen balance of RDX-based aluminized explosives and released more energy. W. A. Trzciński et al.¹⁶ found that AP promoted the combustion of aluminum particles and increased the quasi-static pressure (QSP) in the chamber. The research on the heat of oxidizers continued, and PTFE (polytetrafluoroethylene) with a high fluorine content was also considered as an additive to thermobaric explosives. The test results of M. L. Chan et al.¹⁷ showed that the fluorine-containing material promoted the metal powder to participate in the detonation reaction. Later, M. F. Gogulya et al.¹⁸ studied the explosion of a mixed explosive containing Teflon/Al, and the results also showed that Teflon promoted the oxidation reaction of aluminum powder. Besides, some

studies also mentioned other oxidizers, such as CuO and NH_4NO_3 .

Based on the previous studies, confined explosion tests of HMX-based thermobaric explosives containing oxidizers were carried out in this research. The mechanism of the afterburning reaction and explosion performances were studied by changing the chamber's oxygen concentration and the oxidizer. The in-house developed optical-electrical system recorded the optical radiation of Al_2O_3 and was devoted to studying the combustion process of aluminum particles. Moreover, the pressure data of the blast wave was obtained using a pressure-measurement system. This work aims to increase the combustion rate of a metal fuel and maximize the energy during the afterburning reaction. It can provide a reference for the design of a thermobaric explosive formulation to enhance the afterburning and damage effect.

2 EXPERIMENTAL PART

2.1 Characteristics of the charges

This work studied a total of four formulations of thermobaric explosives. The mixtures consisted of HMX, aluminum powder, oxidizer, binder and other additives, and **Table 1** lists the proportions of their mass fractions. TBX contained 59 % of HMX, while the other three contained 49 % of HMX and 10 % of the oxidizer. The median diameter of dried HMX and spherical aluminum powders was 60 μm and 5.4 μm , respectively. 10 % of KP (30 μm), PTFE (50 nm) and Fe_2O_3 (300 nm) were added to the thermobaric explosives as the oxidizer. In this study, butadiene series rubber ($(\text{C}_4\text{H}_6)_n$) without F (fluorine) was used as the binder for each component. After having mixed the components evenly with the "wet method"^{14,19}, these energetic granules were pressed into cylindrical charges. Each charge was 100 g, and its diameter was 40 mm. Besides, boost charges of RDX-based explosives (pressed into a cylinder, with a mass of 8 g and a diameter of 20 mm) were also prepared. Before the test, the charges of the thermobaric explosive, the booster and the electric detonator were fixed together.

Table 1: Compositions and mass fractions of the thermobaric explosives (w/%)

Name	Composition				
	HMX	Al	Oxidizer	Binder	Others
TBX	59	33	0	5	3
TBX-KP	49	33	10	5	3
TBX-PTFE	49	33	10	5	3
TBX- Fe_2O_3	49	33	10	5	3

2.2 Experimental site

The explosion tests were carried out in a spherical chamber made of composite steel plates. The chamber's diameter was 1400 mm (the volume was about 1.43 m^3), and a test flange was attached to its waist. **Figure 1**

shows the shape and dimensions of the spherical chamber. Four piezoelectric pressure gauges (made of PCB) and a fiber optic sensor were screwed into the flange of the chamber. The signals of the pressure and light were recorded by a data-acquisition instrument (its sampling frequency was 1 MHz). Before the test, the air from the chamber was evacuated by a vacuum pump and then the chamber was filled with a backup gas so that the pressure reached 0.1 MPa. According to the test plan, the selected backup gases and their volume fractions were high-purity nitrogen (99.99 %), dry air (containing 20.95 % of oxygen) and mixed oxygen (50 % of high-purity oxygen + 50 % of dry air). The chamber's gas was evacuated and the chamber was filled with dry air several times to reduce the humidity and remove impurity gases. Therefore, the effect of these impurity gases on the explosion was reduced to a very small degree. The charges were suspended at the center of the spherical chamber and detonated by the electric detonator. Each investigated explosive was used in three tests.

3 RESULTS AND ANALYSIS

3.1 Light emission of Al_2O_3

During the explosion of the thermobaric explosive, aluminum particles were mainly oxidized to Al_2O_3 ,^{14,16} and Al_2O_3 radiated light to the surroundings. Based on the continuous spectrum of condensed phase Al_2O_3 ,²⁰ an optical-electrical system was developed. Then, the optical signals of Al_2O_3 were recorded by the system. During the explosion, the multi-core quartz-fiber optic sensor transmitted the optical signals to the optical-electrical system. The light was first split and filtered, and then, after it was passed through a photomultiplier tube and a photoelectric converter, the light signals were converted into the corresponding voltage signals. After that, the data-acquisition system recorded the voltage-signal output. Considering the test conditions and the performance

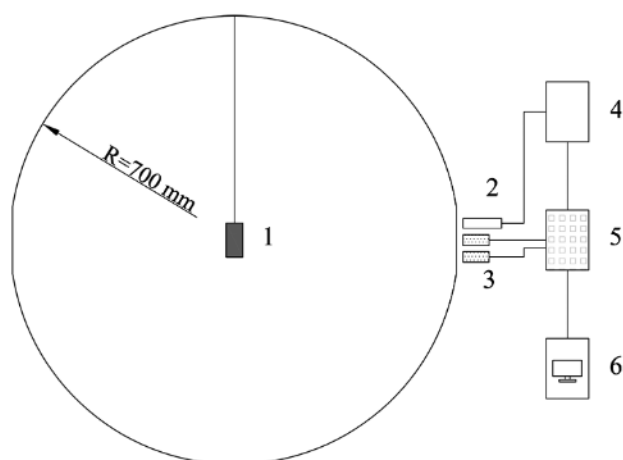


Figure 1: Schematic of the explosion chamber (side view): 1 – explosive charge, 2 – fiber optic sensor, 3 – pressure gauges of PCB, 4 – optical-electrical system, 5 – data acquisition instrument, 6 – computer

of the filter, the filter wavelength used in this study was 700 nm. The principle, steps, mathematical calculations and the correction method of the temperature-measurement system were described in detail in a previous study.²¹

When the explosion started, the high temperature and high pressure caused the oxide film to rupture, and then vaporized aluminum particles escaped from the oxide film. Aluminum particles quickly oxidized to Al_2O_3 after they collided with the explosion field's oxygen and detonation products. The light signals radiated by Al_2O_3 corresponded to the voltage signals. The magnitude and duration of the voltages were reflected by the intensity and time of the combustion reaction of aluminum particles. In the air, the voltage-time curves recorded by the data-acquisition instrument are shown in **Figure 2**. As seen on this figure, the voltages of the four formulations showed a similar trend with time. The voltages appear to increase rapidly at first, then they decrease, and finally they fluctuate slightly. Therefore, this process can be divided into three stages for a detailed description. The voltage increases from zero to the peak in Stage I, the voltage drops from the peak to the valley in Stage II, and the remaining voltage is seen in Stage III.

In Stage I, the voltages of all four samples rose rapidly and reached the peak. Their voltage-curve starting points were the same. One reason for this may be the fact that the oxide layer of aluminum particles absorbed the energy and radiated light after the initiation of detonation reaction; the other reason is that a small part of highly active aluminum particles were rapidly oxidized to Al_2O_3 . The curves in **Figure 2** show that the voltage values of TBX-KP and TBX- Fe_2O_3 reached the peaks earlier than that of TBX. Even if the difference was slight, it means that KP and Fe_2O_3 participated in the combustion reaction of aluminum particles. The peak voltages of TBX-KP and TBX- Fe_2O_3 were 32.7 % and 19.8 % higher than that of TBX, respectively. This showed that KP and Fe_2O_3 had promoted the combustion of aluminum particles to a certain extent so that their reaction in-

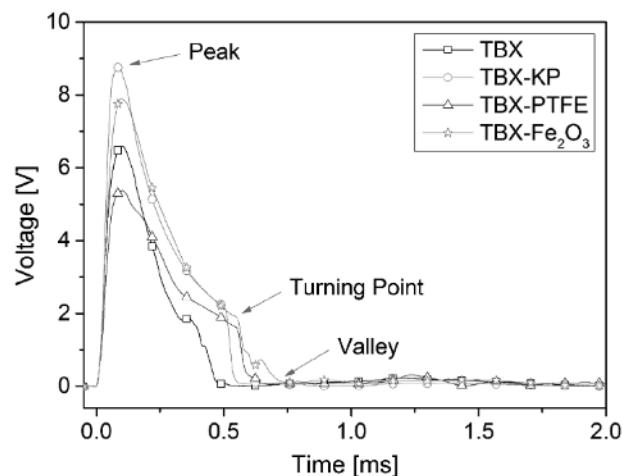


Figure 2: Curves of voltage-time in the air

tensity reached the maximum in a short time. Compared with KP and Fe₂O₃, PTFE had no obvious promotion effect on the intensity of the Al₂O₃ radiation.

In Stage II, the voltages began to decrease at a gradual rate. Compared with the other three samples, the voltage of TBX was the first to drop to the valley. It means that the aluminum particles in TBX burned incompletely, which might have been due to insufficient oxygen. During their voltages reduction, there was a turning point. It showed that the number of aluminum particles still participating in the reaction was very small after this moment. With the afterburning reaction when the voltage dropped to the bottom, the reaction basically ended. In general, the oxidation reaction of aluminum particles was mainly found in Stages I and II, which only lasted for about 500–700 μs. According to the thermite reaction, one Fe₂O₃ molecule can produce one Al₂O₃, while during the reaction of aluminum with O, one KClO₄ molecule can produce 4/3 of Al₂O₃. During this period, the oxygen concentration in the explosion field increased because of the thermal decomposition product (O₂) of KP. This showed that the voltage of KP-TBX had a higher peak and reached the valley earlier.

In contrast, the sample with PTFE did not show any apparent advantages in voltage or time. The reason for this might have been that Al was oxidized to AlF₃ instead of Al₂O₃, and the optical-electrical system did not record the optical radiation of AlF₃. Otherwise, the voltage of PTFE-TBX might have caught up with that of TBX-KP and TBX-Fe₂O₃ with the oxidation reaction of Al and F. A subsequent analysis can further confirm this speculation.

In Stage III, the voltage showed a slight fluctuation because there were a few aluminum particles at the edge of the explosion field participating in the reaction. Simultaneously, a small amount of lower aluminum oxides (Al₂O) converted to Al₂O₃ might have accompanied the process. Alternatively, it might have been that the O in the explosion field was completely consumed, and the

remaining aluminum was idle. In general, the energy released by the reaction at this stage was limited.

These explosive samples were also tested in N₂ (the volume fraction of oxygen accounted for 2.2 %) and O₂ (the volume fraction accounted for 60.5 %) to study the characteristics of the afterburning reaction. Figures 3 and 4 show the results of the optical radiation intensity of Al₂O₃ in N₂ and O₂, respectively.

Assuming the residual oxygen concentration (the volume fraction was 2.2 %) in each test was the same, we temporarily ignored oxygen for this part. The curves shown in Figure 3 were different from that in the air; these curves had only two stages. It means that in the absence of external oxygen, only some aluminum particles were oxidized by the detonation products and oxidizers. The four peaks were all reduced greatly, but the height of TBX-KP was still about 40 % higher than that of TBX, while TBX-Fe₂O₃ was lower than the latter. This result shows that KP could contribute more O to aluminum particles after its thermal decomposition, which enhanced the released energy and prolonged the burning time. The TBX-KP curve, always located above the TBX, reflects this fact, and the former also had a turning point. The durations of TBX-Fe₂O₃ and TBX were very close, but the former voltage was lower than the latter. The reason for this might have been the fact that in the explosion field, gasified aluminum was more likely to collide and react with detonation products (O₂, H₂O, CO₂ and other gases). Still, they had a greater free path with the Fe₂O₃ particles and they were not easy to collide with Fe₂O₃. Surprisingly, the voltage of TBX-PTFE was tiny, and its peak was only 0.1 V. We suspected that this might have been the result of experimental operation errors. Therefore, during this study, we conducted several tests on TBX-PTFE, but the results were similar. They need further confirmation in the future study due to their significant deviation from the expected results.

Figure 4 shows that all the peaks in O₂ increased, and there was an apparent fluctuation (Stage III).

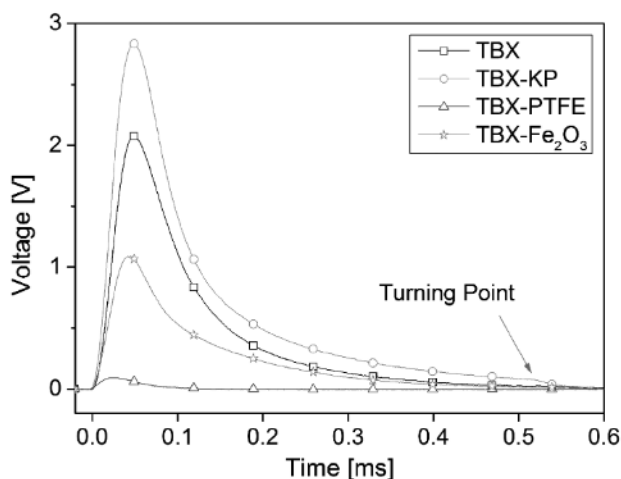


Figure 3: Curves of voltage-time in N₂

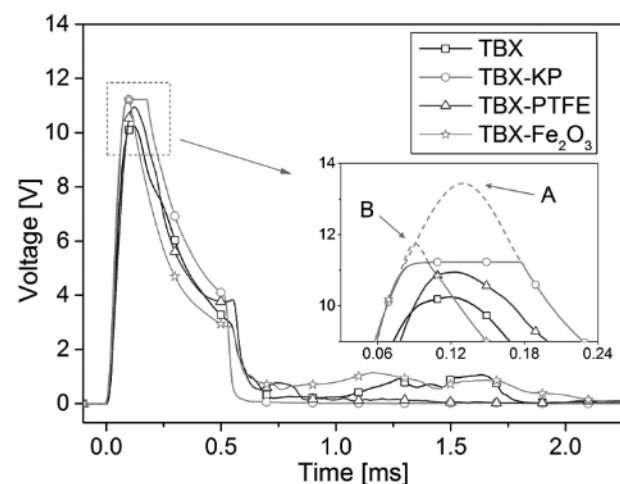


Figure 4: Curves of voltage-time in O₂

Compared with the results from **Figure 2**, it can be seen that the intensity and duration of the Al_2O_3 optical radiation in O_2 were greater than their values in the air. This means that the increase in the oxygen concentration of the environment could further enhance the combustion reaction of aluminum particles. The results also showed that the combustion of aluminum particles in the air was incomplete. Even if TBX-KP, TBX- Fe_2O_3 and TBX-PTFE contained the oxidizer, their combustion reactions were all incomplete. The peaks of TBX-KP and TBX- Fe_2O_3 are not displayed in **Figure 4** because they were beyond the range set of the system. According to their climbing trend, it could be estimated that their peaks were all higher than 11 V, as shown in points A and B. After the peak, it seemed that the energy released by the thermite reaction was lower than that of Al directly reacting with O, which resulted in the curve of TBX- Fe_2O_3 located at the bottom.

In O_2 , the peak of TBX-PTFE exceeded that of TBX, but the slope of the climb was smaller than the latter. It showed that in the early stage of the gasification of aluminum particles, the strong oxidation of F caused a part of aluminum to react with C_2F_4 . This can explain the phenomenon that the voltage of TBX-PTFE in **Figure 2** was lower than that of TBX. Then, once it caught up with TBX and surpassed it, the voltage of TBX-PTFE was above TBX for almost 0.1 ms. It was also worth noting that the time of the turning point was very close, indicating that the aluminum particles oxidized almost completely in O_2 . The TBX-KP turning point appeared in advance and there was almost no apparent fluctuation after the valley, indicating that the thermal decomposition of KP increased the concentration of O, and this slight difference led to a more complete oxidation of aluminum particles in TBX-KP.

In general, it could be seen that the oxygen concentration in both explosives and the environment was critical for the afterburning reaction. Even a slight change in the oxygen concentration could affect the degree of aluminum oxidation. The thermobaric explosives reacted incompletely in the air due to the inefficiency of aluminum oxidation, the content of active aluminum and the oxide layer's thickness. Therefore, an addition of an appropriate amount of oxidizer was beneficial as it increased the oxidation rate of aluminum particles. In this respect, KP showed an apparent promotion effect, and Fe_2O_3 followed.

3.2 Blast characteristics

3.2.1 Intensity of the primary blast wave

The energy of the primary blast wave was mainly derived from the detonation reaction of the thermobaric explosive. It might have also carried a small amount of energy released by the anaerobic combustion of highly active aluminum particles. At a certain moment during the explosion, the speed of the primary blast wave exceeded the expansion speed of the fireball, and then the

blast wave separated from the fireball. After that, the energy released by the combustion reaction of aluminum particles did not enhance the intensity of the primary blast wave. Higher energy indicates that the blast wave could exert a stronger force on the shell of the ammunition and the fragments could obtain a higher flying speed.

In this case, the time difference between the light signals and pressure signals could be a reference parameter to study the intensity of the primary blast wave. After the optical-fiber sensor and the pressure gauges received their corresponding first signal, their time difference between the light and pressure could be calculated. During the explosion (the charge hanging in the center of the chamber), the blast wave propagated outward in the form of a sphere. After the detonation reaction started, the aluminum particles were oxidized to Al_2O_3 , radiating light over a short time. The optical-signal transmission time from the center of the chamber to the optical-fiber sensor was almost negligible. In contrast, the propagation time of the blast wave in the gas mixture became very long. Therefore, when the optical signal arrived, the primary blast wave was still propagating outward. During the test, the positions of the optical-fiber sensor and the PCB pressure gauges were fixed. Moreover, it was assumed that the propagation medium of the blast wave in the explosion field remained the same. The charges must be placed in the center of the spherical chamber to ensure they were at the same distance from the gauges' sensitive surfaces. The deviation of the actual test is within the allowable range.

Figure 5 shows the time differences for the four formulas in three atmospheres. Overall, the time differences of TBX in the three atmospheres were smaller than those of the other three samples. It was the additional HMX (its mass fraction was 10 %) added to TBX that enhanced its energy of detonation reaction. On the other hand, the other three samples with added oxidizers reduced the proportion of HMX, and their intensity of the primary blast wave were reduced significantly. This indi-

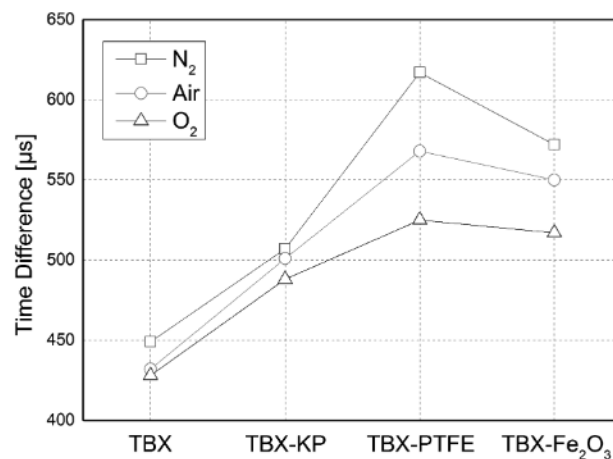


Figure 5: Time difference of light-pressure in three atmospheres

cated that their primary blast waves touched the pressure gauges' sensitive surfaces later than that of the TBX.

It was worth noting that the time differences of TBX-KP, TBX-PTFE and TBX-Fe₂O₃ were closely related to the role of the oxidizers. TBX-KP had the shortest time difference in the three atmospheres. This was because KP could quickly decompose at a lower temperature and contribute energy to the primary blast wave. However, PTFE and Fe₂O₃ only reacted with gasified aluminum after they had absorbed enough heat. The energy released by their oxidation reaction might have been too late to strengthen the primary blast wave. The result was that the wave velocity of TBX-PTFE and TBX-Fe₂O₃ was lower than that of TBX-KP. When only the gas environment was taken into account, the time differences of the four formulations decreased by various degrees as the oxygen concentration in the environment increased. This showed that the intensity of the primary blast wave was related to the oxygen concentration in the environment. It might have been that a higher external oxygen concentration promoted the oxidation of aluminum particles and changed the density of the propagation medium in the explosion field, resulting in an increase in the wave velocity.

3.2.2 Overpressure and the total impulse

The pressure effect of thermobaric explosives was one of the ways of damaging the target. Especially with the primary blast wave, it caused a pronounced damage to the target. Its pressure (the overpressure peak) was an important parameter that reflected the explosion performance. Figure 6 shows typical overpressure-time curves in the air. Points A, B, C and D in Figure 6 indicate the maximum overpressure of the first-wave peak of the four samples (TBX, TBX-KP, TBX-Fe₂O₃ and TBX-PTFE), respectively. The blast-wave propagation characteristics of the four formulations in a limited space were similar. However, some slight differences could be found. The range of 0–1 ms contains the pressure-change process of the primary blast wave. The factor that could affect its

pressure intensity was mainly the energy released by the detonation reaction. The overpressure curves have multiple sharp peaks within tens of microseconds, which means that the energy of the detonation reaction was not released all at once. Instead, it created the primary blast wave in the form of multiple blast waves. Therefore, the pressure recorded by the gauges did not immediately drop to zero.

Then, the blast waves carrying the energy released by the oxidation reaction of the aluminum particles were superimposed on the reflected waves. Within 1–2 ms, the pressure curves of all four formulations fluctuated in a zigzag pattern. This showed that the combustion of aluminum particles was unstable in the heterogeneous explosion field. During this period, there were various chemical reactions, and they were promoted, reacting with each other. The results of the pressure curves show that the peak pressures of TBX-KP and TBX-Fe₂O₃ were higher than those of the other two. This means that the energy released by the reaction of O and F in the oxidizers with the aluminum particles increased the pressure.

Figure 7 shows the average values of the peak overpressure in different atmospheres. According to the results, the overpressure was enhanced by the increase in the oxygen concentration in the environment. In O₂, the overpressure of TBX and TBX-KP was only about 3 % stronger than that in the air. However, their pressure in N₂ was about 28 % lower than that in the air. This means that their overpressure peaks in the air were close to the maximum value, and even excessive oxygen could not make them greatly enhanced. Moreover, the increase in their overpressure peaks in N₂ were suppressed. Besides, the overpressure peaks of TBX were higher than those of the other three samples, and the environmental oxygen concentration did not affect this result. Because of the explosion of an additional 10 % HMX (the mass fraction), the pressure of TBX was enhanced. Considering the energy loss, a part of the energy of the detonation reaction was used to heat PTFE and Fe₂O₃, which resulted in a reduction in the overpressure of TBX-PTFE and

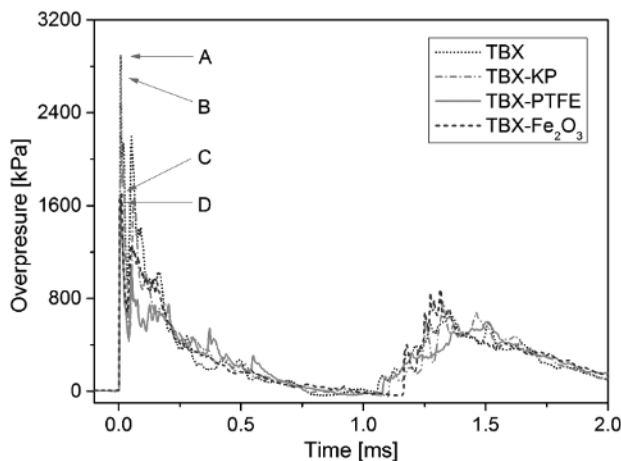


Figure 6: Curves of overpressure-time in the air

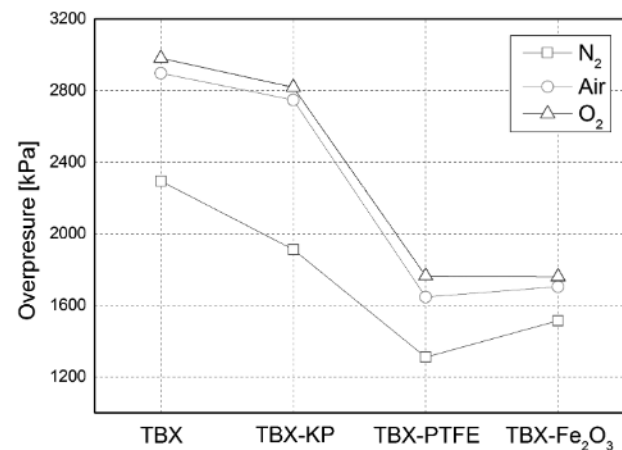


Figure 7: Average values of overpressure peaks in three atmospheres

TBX-Fe₂O₃. In contrast, the thermal decomposition of KP kept the advantage of TBX-KP with a higher overpressure. These results show that the addition of 10 % of KP was more effective than PTFE or Fe₂O₃ in enhancing the pressure effect.

In this study, we quantified the total energy of the explosion in accordance with the blast-wave total impulse within 40 ms. During the confined explosion, the attenuation of energy was mainly related to chemical reactions and heat conduction, assuming that the heat conduction and other heated losses in the test chamber were the same each time. Then, the energy decay could be simplified to be mainly related to the afterburning reaction. For different atmospheres, the average values of the total impulse within 40 ms are shown in **Figure 8**.

The total impulse values of the four formulations showed an increasing trend as the oxygen concentration in the environment increased. This means that the total impulse had a strong dependence on the environmental oxygen concentration. The total impulse of the four formulations in N₂ averaged 49.9 % of that in O₂. This result was obtained in N₂ with a small portion of the remaining air. Therefore, it could be predicted that the energy-release rate of the afterburning reaction was lower than 49.9 % in N₂. The total impulse of TBX in the air was only 84.8 % of that in O₂. This result confirmed again that the O in the air was not enough to oxidize all the aluminum particles,^{11,12,14} and the remaining aluminum was a small part. Compared with TBX, the total impulse of the other three formulations containing oxidizers in the air increased to 96.9 % of that in O₂. The results from **Figures 7** and **8** show that the explosives containing an oxidizer had little effect on the enhancing overpressure, but could significantly increase their total impulse. The reaction of aluminum particles with oxidizers provided additional energy for the subsequent propagation of blast waves. The total impulse of TBX in the air was lower than those of the other three formulations, especially in comparison with TBX-KP when it was about 9 % lower. The addition of KP could increase the

total impulse of TBX-KP by about 9 %. According to a comprehensive comparison, an addition of 10 % of KP (the mass fraction) to a thermobaric explosive could further enhance the total explosion energy.

4 DISCUSSION

The importance of oxidizers should be highlighted because of the inefficiency of the oxidation of aluminum particles. As we all know, AIO was an intermediate for the complete oxidation of Al to Al₂O₃, and more AIO could be emitted if there were enough oxygen in the atmosphere.¹¹ Therefore, an increase in the oxygen concentration inside the explosive was conducive for enhancing the optical radiation intensity of Al₂O₃.

In this respect, the thermal decomposition reaction of KP was advantageous for increasing the oxygen concentration. When KP was combined with Al (KClO₄+2Al → KCl+1/2O₂+Al₂O₃), a part of O remained after Al₂O₃ was formed. However, the thermite reaction (2Al+Fe₂O₃ → Al₂O₃+2Fe) could not produce oxygen. Alternatively, its product of Fe might still have grabbed external O with Al. Compared with the former two, the amount of Al₂O₃ of TBX-PTFE became small due to the oxidation reaction of PTFE and Al (C₂F₄ + 4/3Al + 2O₂ → 4/3AlF₃ + 2CO₂). The presence of oxidizers affected the light radiation intensity and duration of Al₂O₃; these facts are reflected in **Figures 2** and **3**. The detonation reaction of an explosive mainly provided the energy to the primary blast wave. During these short periods, the formulation could additionally contribute energy, its blast wave reaching the gauges earlier while showing a higher overpressure peak. **Figures 5** and **7** show these results. After that, the energy of the afterburning reaction was mainly used to maintain the subsequent blast-wave propagation and increase the heat of the fireballs. These reactions proceeded to increase the total impulse of the explosion, as shown in **Figure 8**. In summary, KP had a more significant advantage in enhancing the pressure effect and heat effect.

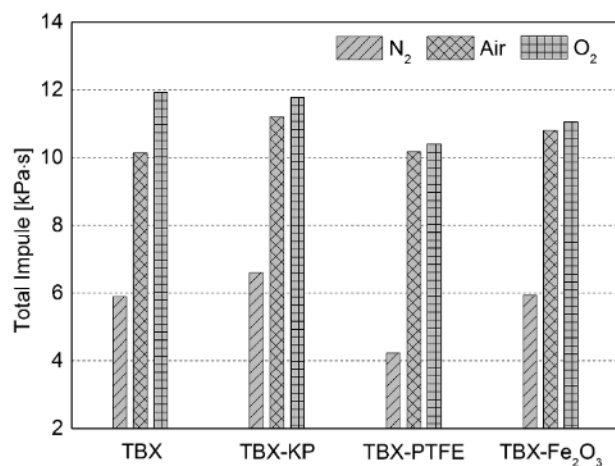


Figure 8: Average values of the total impulse in three atmospheres

5 CONCLUSIONS

In this study, confined explosions of HMX-based thermobaric explosives containing KP, PTFE, and Fe₂O₃ were studied. The conclusions are as follows:

1. The in-house developed optical-electrical system can record the light radiation of Al₂O₃ and reflect the oxidation process of aluminum particles. Aluminum particles (5.4 μm) show a strong dependence on the oxygen concentration in the environment. Increasing the oxygen concentration can prolong the oxidation duration of Al and enhance the optical radiation intensity of Al₂O₃. The optical-radiation results of Al₂O₃ in O₂ and air show that aluminum particles (the mass fraction was 33 %) are not completely oxidized in the air, and the oxidation duration is 500–700 μs.

2. The intensity of the primary blast wave and the total impulse increase with the increase in the oxygen concentration in the environment. The enhancement of the overpressure peak is suppressed in N_2 , but it is not sensitive to the atmosphere of O_2 . The total impulse of the thermobaric explosive without an oxidizer in the air is only 84.8 % of that in O_2 .

3. Increasing the oxygen concentration of the explosive can further enhance the total impulse, especially the addition of 10 % of KP can increase the total impulse by about 9 %.

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