Effect of storage temperature on explosion characteristics of RDX-based thermobaric explosive

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Abstract. The effect of storage temperature on explosion characteristics of the free space explosion of RDX-based thermobaric explosives was studied, and the fireball and the overpressure were obtained. The results showed that the temperature and the volume of the fireball can reach 2400 K and 400 m³ respectively. Low temperature and temperature shock will reduce the temperature and the volume of the fireball and the overpressure. In addition, the aluminum powder does not burn completely, and the time to reach the maximum temperature will be delayed by at least 33 ms. The high temperature can slightly enhance the thermal effect and the pressure effect.

1. Introduction

The combat environment in modern warfare is very complicated, and harsh environments with rapid temperature changes are inevitable. In this case, the ammunition would subject to heat during the period of storage, transportation, and use. Especially in the desert, the ammunition would impact by high and low temperature in a short time, due to the large temperature difference between morning and evening. Because of thermal effects, the ammunition itself may have undergone a slow physical change or chemical reaction, causing thermal aging [1]. During the press of thermobaric explosives, micro-cracks have been present in the charge [2-3]. After continuous stimulation by heat, micro-cracks may grow into wider cracks or even break. The damage caused by this thermal effect would affect the structure and performance of the charge. In addition, damage has an effect on the formation of "hot spots", which in turn affects the explosion characteristics of explosives [4]. Elban W L [5] studied the micro structure of explosives after effects of high and low temperatures, and observed the micro cracks and trans granular fracture. The literature [6-9] showed that the detonation speed of PBX has a tendency to decrease due to thermal damage tests. Urtiew P A [10] found that the LX-17 explosives were more sensitive after thermal cycling. These papers provide a theoretical basis of studying the effects of heat on the structure and mechanical properties of explosives. However, the study of the explosion characteristics of damaged explosives is also very important, which helps to grasp the actual combat effect of ammunition.
In this paper, the charges of RDX-based thermobaric explosives were stored in incubators at different temperatures to simulate the harsh environment in the battlefield. Then, the explosion test was conducted in free space, and the pressure and the growth process of the fireball was recorded. Based on overpressure, temperature and volume of the fireball, the effects of storage temperature on pressure, thermal and afterburning reaction have been investigated. This work could provide a reference for the formulation design and storage temperature of thermobaric explosive.

2. Experiment

2.1. Charge characteristics and storage temperature
In this paper, RDX-based thermobaric explosives were pressed into hollow charges. The shape and size of the test charges are shown in figure 1. A booster can be embedded in the hollow position of the thermobaric explosive, and then it can be detonated by an electric detonator. Each charge of thermobaric explosive had a mass of 2.5 kg and a density of 1.92 g/cm$^3$. The booster was 328 g and the density was 1.68 g/cm$^3$.

![Figure 1. Test charge: 1-Electric detonator, 2-booster, 3-thermobaric explosive.](image)

Before the test, the charges of thermobaric explosives were stored in four incubators with different temperatures, and there are 4 charges in each incubator. The storage mode and temperature of charges were listed in table 1. It should be noted that boosters were not stored in the incubator. After the charges were restored to 25 °C, the explosion tests were performed immediately.
Table 1. Storage mode and temperature of charges.

| Name   | Mode              | The temperature and duration of storage                                                                 |
|--------|-------------------|---------------------------------------------------------------------------------------------------------|
| TBX-G1 | Normal temperature| The charges were store at 25 °C for 48 h.                                                               |
| TBX-G2 | High temperature  | After being stored at 65 °C for 48 h, the charges were restored to 25 °C.                                |
| TBX-G3 | Low temperature   | After being stored at -50 °C for 48 h, the charges were restored to 25 °C.                              |
| TBX-G4 | Temperature shock  | After being stored at 65 °C for 2 h, the charges were transferred to a -50 °C incubator within 5 min. After holding for 2 h, they were transferred to a 65 °C incubator again. After repeating this cycle 3 times, the charges were restored to 25 °C. |

2.2. Experimental site

The explosion test was conducted in free space, and the charges were fixed at a distance of 1 m from the rigid ground. Taking the axis projection of the charge as the center, the pressure gauges were arranged at a radius of 5 m and 7 m, as shown in figure 2. There were two types of pressure gauges produced by PCB company, which measure the pressure of reflected blast waves and air blast waves, respectively. The former were buried in the ground, and their sensitive surface was flush with the ground. The latter was fixed on the same horizontal plane at 1 m from the ground, and they were flush with the charge. The pressure signals were recorded by a data acquisition instrument, and the sampling frequency was set to 1 MHz.

Meanwhile, an infrared thermal imager made in Japan was used to record the fireball. The temperature range of the imager is -60-2000 °C, and the maximum frame rate is 30 Hz. But the temperature of the fireball is higher than 2000 °C, so its actual temperature needs extra calculation. Calibration of the imager and calculation method of fireball was described in detail in the paper [11]. Because the frame rate of the imager was relatively low and the outline of the fireball cloud image was not clear enough, a high-speed camera was added to record the features and global shape of the fireball. The model of the high-speed camera was Vision Research V210, and the sampling frequency was set to 2000 Hz. The imager and camera were fixed behind the explosion-proof wall and the horizontal distance from the explosion center was 45m. It should be noted that their lens was 1 m from the ground and were faced the charge. In addition, in order to calculate the actual size of the fireball, a 5 m post was placed vertically at the center of the explosion before the test, and it was evacuated after recorded by the high-speed camera.
3. Results and analysis

3.1. Fireball

3.1.1. Fireball temperature During the explosion of thermobaric explosive, it can be divided into three stages: anaerobic detonation, anaerobic combustion and afterburning reaction. It therefore has a significant thermal effect because of the oxygen in the air is used to increase energy. The first two stages lasted hundreds of microseconds in total, that is, the second stage had ended within 1 ms, and the third stage (afterburning reaction) had begun. However, the maximum frame rate of an infrared thermal imager is 30 Hz, which is much longer than the duration of the first two stages. Therefore, the recorded features and global shape of the fireball can be considered as the third stage.

The typical fireball infrared cloud image of TBX-G2 is shown in figure 3. It can be seen from figure 3 that the shape of the fireball was irregular and had obvious temperature gradations. As time went on, the high temperature area (red part) of the fireball gradually shifts to the upper right. This might be due to cracks in the charge, which caused the aluminum powder to be scattered unevenly [11]. After 198 ms, the temperature of the fireball decreased rapidly, but the temperature in a large range was still higher than the surrounding environment. It is also known that the duration of the fireball can be up to hundreds of milliseconds.

Figure 2. Schematic illustration of experimental layout: 1-explosive charge, 2- PCB pressure gauges of reflected shock wave, 3-PCB pressure gauges of air shock wave, 4-high-speed camera, 5-infrared thermal imager, 6-explosion-proof wall.
Figure 3. The typical fireball infrared cloud image of TBX-G2.

The highest fireball temperature in each group was selected for comparative analysis, and the change of the fireball temperature with time is shown in figure 4. The curves showed that the temperature first increases and then decreases. At the 33 ms, the fireball temperature of the four kinds of charges exceeded 1800 K and continued to increase, indicated that the aluminum powder had not yet fully burned. After reached the highest temperature, it showed a decreasing trend, which means that the content of aluminum powder was decreasing. During the growth of the fireball, the temperatures of TBX-G1 and TBX-G2 were close, and the highest temperature could reach 2400 K. In addition, their temperature has always been greater than the TBX-G3 and TBX-G4. The maximum temperatures of TBX-G3 (2271.4 K) and TBX-G4 (2224.5 K) were lower than that of TBX-G1 (2427.7 K) by 6.8% and 9.1%. Furthermore, the time for the latter fireball to reach the highest temperature was lagging, which was about 33 ms and 66 ms behind the TBX-G1, respectively. The TBX-G4, in particular, reached its maximum temperature in 132 ms, but the temperature was still the smallest. This means that low temperatures and temperature shocks caused more serious damage to the charges, and this damage delayed the afterburning reaction and reduced its energy. At 363 ms, the fireball temperature of the four kind of charges was still higher than 1200 K. It showed that the thermal effect in the afterburning reaction stage was very significant. The combustion of aluminum powder can promote the temperature and duration of the fireball. But the effects of low temperature and temperature shock on afterburning reaction were opposite.

Figure 4. Changes of temperatures with time.
The method described in the paper [12] was used to study the temperature distribution in the fireball, and set the emissivity to 1. The infrared clouds at the highest temperature of the four kinds of charges are shown in figure 5. Take the point with the highest temperature as the intersection point on the cloud image, and made a vertical line and a horizontal line perpendicular to each other through the intersection point. The length of the line can be calculated based on the actual size of the fireball. It can be seen from figure 5 that the shape of the fireball and the position of the intersection point were different. There was no obvious symmetry in the internal distribution of the fireball, but the highest temperature areas were all in the upper right. This shows that, in the stage of afterburning reaction, the distribution of the mixture in the explosion field was uneven.

![Figure 5. Infrared cloud image of the highest temperature.](image)

Temperatures at different distances on the vertical and horizontal line are shown in figure 6 and figure 7. It can be seen from figure 6 that the high temperature area was concentrated in the upper part of the fireball, and there was a smaller peak in the lower part. This means that the temperature on the vertical line did not increase monotonically and then decreases, but had multiple peaks and had a certain level. It can also be known that the position of the temperature peak of TBX-G2 was relatively low on the vertical line, while the TBX-G4 was the opposite. It can be inferred that high temperature was beneficial to the rapid combustion of aluminum powder, but temperature shock did not showed this effect. The high temperature areas were biased to the right of the fireball, but the temperatures of TBX-G1 and TBX-G2 showed a trend of high on both sides and low in the middle, as can be seen from figure 7. In sharp contrast, the temperatures of TBX-G3 and TBX-G4 were more evenly distributed on the horizontal line. This might be related to the fact that low temperature and temperature shocks slowed down the burning rate of aluminum powder. In addition, the height and width of the fireball could reach 11 m and 13 m respectively. The size of the fireball was conducive to expanding the scope of the thermal effect.
3.1.2. Fireball volume Based on the pictures recorded by the high-speed camera, the volume of the fireball was calculated using Auto CAD. Due to the irregular shape and high brightness, the boundaries of the fireball were blurred and difficult to determine accurately. The deviation in the calculation of the fireball volume was existed, but the change trend of the fireball can still be obtained. The change of the fireball volume over time is shown in figure 8. Obviously, the volume of fireballs tended to decrease-increase-decrease over time. After the detonator detonated, the booster exploded before the thermobaric explosive, which also had fireballs. During the reduction of the booster fireball, the thermobaric explosive also exploded and quickly reached a stable detonation. These two stages occurred almost simultaneously, but there was still a time difference. At this time, only a small part of the aluminum powder was burned, and the fireball had a certain hysteresis (compared with the chemical reaction of the mixtures), so the fireball volume had decreased within 30 ms.

It also reflected that the afterburning reaction started late but lasted a long time. After that, the fireball continued to grow and expand, and quickly decreased after reached the maximum volume. The rapid burning of aluminum powder resulted in its large amount being consumed and was insufficient to continue the growth of the fireball. The maximum volume of the fireballs of TBX-G1 and TBX-G2 exceeded 400 m$^3$. But the time for the latter's fireball volume to reach its maximum was shorter, which
matched its fastest temperature rise. High temperature increased the expansion rate of the fireball, but this effect was slight. Figure 8 also showed that the fireball volume of TBX-G3 and TBX-G4 has been smaller than TBX-G1, and the maximum volume was lower than the latter by 43.7% and 16.2%, respectively. This proved that the low temperature and temperature shock inhibited the growth and expansion of the fireball. Especially at low temperatures, the efficiency of the afterburning reaction was greatly reduced. This meant that there was still a certain amount of aluminum powder that had not been fully burned.

![Figure 8. Changes of the fireball volume over time.](image)

3.2. Overpressure

Even with pressure gauges at the same distance from the center, the measured overpressure peaks were not equal. This difference might be related to the heterogeneous thermobaric explosive and the gauge itself. Therefore, the mean of the overpressure peaks of the reflected blast wave and the air blast wave at a distance of 5 m and 7 m were calculated, and they are shown in figure 9. The results showed that compared with the air blast wave, the reflected blast wave had a higher overpressure peak at 5 m and 7 m. Regardless of the storage temperature, the peaks of reflection overpressure and air overpressure of the TBX-G1 at 7 m were 68.6% and 33.6% lower than that at 5 m, respectively. This meant that the reflected blast wave decayed faster than the air blast wave within the same propagation distance. Considering the storage temperature, the reflection overpressure at 5 m, the TBX-G2 was 2.5% higher than the TBX-G1, but the TBX-G3 and the TBX-G4 were 12.4% and 16.2% lower than the TBX-G1, respectively. The reflection overpressure at 7 m had a similar trend, but the difference was small. It has been proven that the storage temperature affected the overpressure of the charges. In addition, high temperature could slightly increase the reflection overpressure, but the amount of this increase was very small. In contrast, low temperatures and temperature shocks significantly reduced reflected overpressure. Obviously, protecting the ammunition from thermal effects is conducive to the release of explosion energy.
4. Discussions

According to the law of solid heat conduction, the temperature inside and outside the charge is consistent. When the ambient temperature changes, the charge conducts heat from the outside to the inside. If this change is rapid, tensile stress would be generated inside the charge because the external temperature transfers heat slowly to the center. The tensile stress generated by the thermal effect causes irreversible plastic deformation of the charge. When this stress is greater than the tensile limit of the charge, the crack will further expand. The damage caused by the continuous development of cracks directly affects the explosion energy.

It can be inferred from the test results that the damage caused by the low temperature and temperature shock to the explosive was greater. In addition, the binder might detackify because of the thermal effect, so that the cracks of the charge were further enlarged. As a result, the energy of the explosion was reduced, manifested in lower overpressure and temperature. Meanwhile, the combustion of aluminum powder was also limited. It took longer time for the fireball to reach the maximum temperature, and the volume of the fireball was reduced. Compared with the former two, the effect of high temperature on explosives was smaller. Moreover, it may had a weak promoting effect on increasing overpressure. This may be related to the high temperature promoted the formation and spread of hot spots in charges. Overall, the temperature changes are detrimental to the fireball and pressure of thermobaric explosives. As for the specific cause of this difference, more tests and methods are needed to verify and analyze it. More research work in this paper will be carried out, and it is expected to obtain the mechanism of the thermal effects on explosives.

5. Conclusions

In this paper, the free space explosion test of RDX-based thermobaric explosive stored in different temperature was performed. After analyzing the results, some conclusions are summarized:

(1) The fireball can last for hundreds of milliseconds, and its maximum temperature can reach 2400 K. Low temperature and temperature shock will reduce the fireball temperature by more than 6%, and the time to reach the maximum temperature will be delayed by at least 33 ms.

(2) The internal distribution of fireballs has no obvious symmetry, but have a certain level. The
maximum volume of the fireball can reach 400 m³, and the storage temperature will affect the features and global shape of the fireball. Especially at low temperature and temperature shock, their volume is reduced by 43.7% and 16.2% respectively compared to the normal temperature.

(3) The storage temperature affects the pressure, especially the overpressure of reflected blast wave at 5 m. Compared with the normal temperature, the overpressure of the low temperature and the temperature shock decreased by 12.4% and 16.2%, while the high temperature does not show this trend.

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