Experimental research on thermal ignition of typical shell aluminized mixed explosive under fast thermal action

S W Zhao¹, G Zhou¹ and C L Wang¹

¹ Northwest Institute of Nuclear Technology, Xi’an 710024, Shanxi, China

Abstract: In order to obtain the thermal ignition characteristics of the typical aluminized mixed explosive with shell under fast thermal action, this research takes the casting TNT RDX AI (THL) explosive and casting PBXN-109 explosive as the research target, and establishes the thermal ignition experiment platform for fast heating shell explosives and thermal ignition model of explosive with shell, and carries out the thermal ignition experiment of two explosives under different sizes. It uses the fast heating device to generate fast thermal action, and heat the explosives in steel restraints, which uses the thermocouple to tests the temperature history to obtain the explosion temperature and delay time of the explosive thermal ignition. The results show that: ① The explosion temperature and delay time of the two kinds of explosives increase with the ratio of heating range to explosive size decrease, and both of them are larger than the 5s brustpoint. ② In a certain error range, the model calculation values and experimental results are basically consistent, which can be used for semi quantitative predicting explosion temperature and delay time. ③ THL explosive is casting type with high density and high hardness, which damaged greatly after thermal ignition. PBXN-109 explosive is a casting plastic bonded explosive with low density and soft quality, and its damage is not so serious as the THL explosive after thermal ignition.

1. Introduction

In the development of national defense weapon equipment, aluminized explosive is widely used as various warhead charges, thus forming the shell explosive combination of metal shell and aluminized explosive. In the process of ammunition storage, transportation and test, due to fire accidents and other reasons, the metal shell may be subjected to the fast thermal action of fire baking (such as 6 mm thick steel plate, reaching 700 °C in 2 mins.) [1].

There are a large number of theoretical and experimental researches for the explosive thermal ignition at home and abroad. In 1939, Soviet scientist Zeldovich first discussed the issue of thermal ignition, extended the theory of thermal explosion steady state to flat containers with different temperatures on the wall, and determined the critical conditions of thermal ignition in this system; In 1958, Cook and Hicks performance further calculation of the thermal ignition phenomenon, which involved the effects of various parameters on the ignition delay [2-3]. The monograph "Thermal Explosion Theory" and "Thermal Ignition Theory" published by Professor Feng Changgen from Beijing Institute of Technology systematically summarized the research results of thermal explosion and thermal ignition at home and abroad [4-5]; Wang Liqiong, Feng Changgen, and Du Zhiming...
edited and published "Theory and Experiment of Explosion and Ignition in Finite Space", which summarized the theoretical research and experimental results of two-dimensional thermal explosion, thermal ignition, shock wave ignition, and laser ignition [6].

However, the research on the thermal ignition of shell aluminized mixed explosive under the fast thermal action has not been reported in the relevant public literatures. Therefore, it has important academic value, engineering value and military value to conduct the experimental research on the thermal ignition of shell aluminized mixed explosive under fast thermal action. This research takes improving the ammunition safety as the background, and the research conclusion can be directly used to guide ammunition protection.

This research performs thermal ignition experimental researches of two typical aluminized mixed explosive under the fast thermal action, including casting TNT RDX Al (THL) explosive and casting plastic bonded explosive PBXN-109 explosive. On the thermal ignition experiment platform of fast heating shell explosive, it adopts self-developed fast heating device to generate the fast heat input condition, and uses the nickel chromium and silicon thermocouple to test the temperature history. It obtains the thermal ignition explosion temperature and delay time of two kinds of explosives happened under different size conditions, determines the explosion temperature and delay time of thermal ignition of two kinds of explosives increase with the ratio of heating range to explosive size decrease. In addition, the mathematical model of shell explosive thermal ignition is established; which takes this model as the basis to calculate the explosion temperature and delay time of two kinds of explosives under experimental fast heating input conditions. Compared with the experimental data, the model can be used to semi quantitatively predict the temperature and delay time of thermal ignition explosive in a certain error range.

2. Thermal Ignition Experiment Platform of Fast Heating Shell Explosives

2.1. Platform structure

The platform consists of two parts: experimental device and test system. The experimental device includes a fast heating device, explosive and explosive restraint cylinder; the heating device produces a fast thermal effect, and the restraint cylinder generates restraining conditions; the test system is temperature measuring system, and experimental platform composition is shown in figure 1. The explosive restraint cylinder is made of 45 # steel bar. One end is blind hole and the other end is opening. The opening surface and cover plate are connected and fastened by bolts. The cylinder is filled with explosives, and the restraint cylinder structure is shown in figure 2. The fast heating device heats the blind hole-end of the explosive restraint cylinder to provide the heat input conditions for the internal explosive to generate thermal response; the temperature sensor is set on the metal wall at the bottom of the explosive to measure the temperature history, and the experimental layout is shown in figure 3.
Figure 1. Thermal ignition experimental platform composition.

Figure 2. Restraint cylinder structure.

Figure 3. Experimental layout.

2.2. Fast heating device
The fast heating device adopts high-energy solid fuel-injection heating principle, and uses high-temperature gas generated by the high-energy solid fuel to heat. The action range is Φ 60mm, and the heating time is divided into 5s and 10s. The heating device structure is shown in figure 4. The fast heating device uses the heating effect plate to obtain the temperature history of back wall of effect plate to determine heating device effect. The effect plate is a steel plate with side length of 300 mm × 300 mm and thickness of 8 mm, 13 mm and 20 mm respectively, as shown in figure 5 Experimental layout. It uses the nickel chromium and silicon thermocouple temperature sensor to test the temperature history at the back of the steel plate and the typical temperature history of back surface of the effect plate is shown in figure 6. The marked distance of the curve in the figure is from the measuring point to the center point. The temperature history peak value and corresponding time are shown in table 1.

Figure 4. Heating device structure.  Figure 5. Calibration experiment layout.
Figure 6. Typical temperature history curve.  
(duration: 10s, range: Φ 60mm, effect plate thickness: 8mm)

Table 1. Temperature history peak value.

| Heat source type | Effect plate thickness/mm | Peak temperature/℃ | Corresponding time/s | Temperature rise rate/(℃/s) |
|------------------|---------------------------|---------------------|-----------------------|---------------------------|
| 5 s, Φ60 mm      | 8                         | 1196                | 8.5                   | 140                       |
|                  | 15                        | 1011                | 16                    | 63                        |
| 10 s, Φ60 mm     | 20                        | 641                 | 22                    | 29                        |
|                  | 25                        | 565                 | 27.5                  | 21                        |

It can be seen from the calibration data that the heating time is 5 s, the max. temperature at the center point is 1196℃, the time to reach the max. temperature is 8.5 s, and the average temperature rise rate is 140℃/s; When heating time is 10 s, the max. temperature at the center is 1011℃, the time to reach the max. temperature is 16 s, and the average temperature rise rate is 63℃/s; From the point of view of the maximum temperature and temperature rise rate, the heating equipment can achieve rapid heating effect of the steel plate.

2.3. Temperature test system

The temperature test system consists of: Ni Cr Ni Si thermocouple → compensation wire → voltage amplifier → cable → data acquisition system → cable → acquisition computer. Figure 7 sketch temperature test system, and figure 8 photograph of temperature test system.

Figure 7. Sketch temperature test system.

Figure 8. Photograph of temperature test system.
3. Experimental Results and Analysis

Perform the thermal ignition experiments of (THL) and PBXN-109 explosive thermal ignition 5 times. The THL explosive is filled by casting, and its components are TNT, RDX and AL, and the mass ratio is 60%, 24% and 16%; The PBXN-109 explosive is filled by casting that consists of RDX, AL, DOA, HTPB and additives, and the mass ratio is 65%, 20%, 7%, 7% and 1% [7-8].

The heating time of the heating device is 5s and the heating range is Φ60mm; the explosive size is divided into Φ100mm × 20mm and Φ50mm × 20mm, and the masses are ~265g and ~65g. The experimental layout is shown in figure 9 and the thermocouple layout location is shown in figure 10. The experimental data summary is shown in table 2. The typical temperature history curve is shown in figure 11. After experiment, the real object of the explosive restraint cylinder is shown in figure 12, and the thermal ignition burst temperature varies with the explosive size shown in figure 13.

![Figure 9. Experiment physical layout.](image1)

![Figure 10. Thermocouple layout.](image2)

![Figure 11. Typical temperature history curve.](image3)
Figure 12. Real object of restraint cylinder after experiment.

Table 2. THL explosive thermal ignition experimental data.

| Explosive type | 5s Burst point | Explosive size and quality | Heating range / Explosive diameter | Thread restraint strength (MPa) | Burst temp (℃) | Delay time (s) | Macro destruction |
|----------------|----------------|---------------------------|-----------------------------------|-------------------------------|----------------|----------------|------------------|
| THL            | 270 °C         | Φ 5cm 65g                 | 1.2                               | ~100                          | 350℃           | 3              | The cover plate is convex and deformed, and its fastening thread is broken. |
|                |                | Φ 10cm 265g               |                                   |                               | 356℃           | 3 ~3           |                  |
|                |                |                           |                                   |                               | 368℃           | 3              |                  |
|                |                |                           |                                   |                               | 575℃           | 4.8            | The cover plate is convex and deformed, and its fastening thread is broken. |
|                |                |                           |                                   |                               | 491℃           | 5.5            | ~5               |
| XN -109        | 282 °C         | Φ 5cm 65g                 | 1.2                               | ~100                          | 304℃           | 2.8            | The cover plate is convex and deformed, the fastening thread is intact without dropping. |
|                |                | Φ 10cm 265g               |                                   |                               | 324℃           | 2.9            | ~3               |
|                |                |                           |                                   |                               | 325℃           | 3.3            |                  |
|                |                |                           |                                   |                               | 365℃           | 4.5            | ~5               |
|                |                |                           |                                   |                               | 391℃           | 4.5            | The cover plate is convex and deformed, the fastening thread is intact without dropping. |

Figure 13. Thermal ignition burst temperature varies with the explosive size.
By analyzing the restraint cylinder damage situation after the experiment, it can be concluded that:

1. THL explosive: when the size is $\Phi$ 50mm $\times$ 20mm, the cover plate bulges and deforms after the explosive thermal ignition explosion, and the cover plate fastening thread breaks; When the size is $\Phi$ 100mm $\times$ 20mm, one cover plate bulges and deforms, one cover plate bulges and deforms, and the fastening thread breaks; the other cover plate bulges and deforms, and the fastening thread is intact without dropping. It shows that the chemical reaction after the thermal ignition is more intense, and the shock wave produced by explosion will break the bolt and deform the cover plate, but the intensity is not the same. 2. PBXN-109 explosive: When the size is $\Phi$ 50mm $\times$ 20mm, the cover plate bulges and deforms after explosive thermal ignition explosion, and the fastening thread is intact without dropping; When the size is $\Phi$ 100mm $\times$ 20mm, the same cover plate bulges and deforms, and the fastening thread is intact without dropping.

Besides, comparing the restraint cylinder damage situation of the two kinds of explosives experiments, it can also be concluded that THL explosives are fused cast, with high density and hardness, and it damaged seriously after thermal ignition. The PBXN-109 explosive is cast-type plastic bonding explosive with low density and soft quality, and its damage is less serious than that of THL after thermal ignition.

Analyzing that the burst temperature varies with the explosive size, we can get: 1. THL explosives: the size is $\Phi$50mm $\times$ 20mm, namely, the ratio of heating range to the explosive size is 1.2, the explosive temperature under fast thermal action is higher than 5s explosive point of the explosive - 80 °C; The size is $\Phi$100mm $\times$ 20mm, namely, when the ratio of the heating range to explosive size is reduced to 0.6, the burst temperature and delay time under fast heating action are significantly increased, and the average value is higher than the 5s explosive point- 263 °C. The explosion temperature varies with the explosive size, as shown in figure 13 (a). 2. PBXN-109 explosives: When the size is $\Phi$ 50mm $\times$ 20mm, the explosive temperature under fast thermal action is close to the 5s explosive point of the explosive, and the average value is higher than the explosive point ~ 36 °C. When the size is $\Phi$100mm $\times$ 20mm, the burst temperature and delay time under rapid thermal action also increase, the average value is higher than the explosive point of 5s ~ 96 °C; the burst temperature varies with the explosive size, as shown in figure 13 (b). Therefore, the thermal ignition burst temperature of TNT RDX Al explosive and PBXN-109 explosives are both higher than the 5s burst point under the fast heat action; Besides, the burst temperature and the delay time increase with the explosive size ratio decrease.

4. Shell Explosive Thermal Ignition Model and Verification

4.1. Mathematical model of shell explosive thermal ignition

In 3D rectangular coordinate system, the Fourier heat conduction equation without internal heat source is used to describe the heat conduction process inside the metal plate under the fast heating action, and the Fourier heat conduction equation with internal heat source term is used to describe the explosive thermal response process. The internal heat source is expressed by Arrhenius reaction rate, and the thermal ignition model of shell explosive under the fast heat action is established. The mathematical model expression is equation group (1), and figure 14 is the schematic diagram of shell explosive under fast thermal action.
Figure 14. Shell explosive under fast heating action.

\[
\begin{align*}
\rho \alpha c_1 \frac{\partial T_1}{\partial t} &= \kappa \frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} + \frac{\partial^2 T_1}{\partial z^2} \quad 0 < x < l_1 \\
\rho_2 c_2 \frac{\partial T_2}{\partial t} &= \kappa_2 \frac{\partial^2 T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} + \frac{\partial^2 T_2}{\partial z^2} + \rho_2 Q \cdot e^{-\frac{E}{RT}} \quad l_1 < x < l_2
\end{align*}
\]  

(1)

In the formula, \( T \) is temperature, \( \rho \) is density, \( c \) is specific heat, \( \kappa \) is thermal conductivity and \( t \) is time, the subscripts 1 and 2 represent steel shell and explosive respectively, and \( Q \), \( E \), \( A \) are reaction heat, activation energy and pre-exponential factor of explosive respectively, the \( R \) is gas constant, \( l_1 \) and \( l_2 \) are shell thickness and explosive thickness respectively.

The initial conditions are:

\[ t = 0, \quad 0 < x < l_2 : T_1 = T_2 = 0 \]  

(2)

The boundary condition is:

\[ x = 0, \quad y < r_0, \quad z < r_0, \quad \kappa_1 \left( \frac{\partial T_1}{\partial x} + \frac{\partial T_1}{\partial y} + \frac{\partial T_1}{\partial z} \right) = -I \]  

(3)

In the formula, the \( I \) is the thermal input condition power density.

The critical condition is:

\[ \frac{\partial T}{\partial t} \rightarrow \infty \]

4.2. Thermal effect simulation of fast heating device

It adopts ANSYS calculation software, and uses the Fourier heat conduction equation without internal heat source to describe the heat conduction process in the metal plate under fast heating action. Numerically simulate the heat conduction process of the fast heating device effect to substitute the 45# steel thermo-physical properties into the equation to obtain the temperature history curve of the effect plate back wall. The simulated temperature distribution cloud chart is shown in figure 15. Comparing the measured back wall temperature data with the calculated data, they are basically the same, so as to determine the heat input power density in the boundary conditions of shell explosive thermal ignition model, and the typical comparison curve is shown in figure 16.
4.3. Shell explosive thermal ignition model and verification

It uses the shell explosive thermal ignition model to analyze the explosive thermal ignition delay time inside the pipe, and the physical and chemical parameters of THL explosive and PBXN-109 explosives are shown in table 3, and establish the 1/4 model, and the model temperature distribution is shown in figure 17. The comparison of experimental values and calculated values of explosive thermal ignition temperature and corresponding delay time is as table 4, and the comparison between the experimental value and the calculated value of the typical thermal ignition temperature curve is shown in figure 18.

Table 3. Explosive Physical and Chemical Parameters.

| Explosive | Density ρ/(kg · m⁻³) | Thermal conductivity κ/(W · m⁻¹ · K⁻¹) | Specific Heat c/(J · kg⁻¹ · K⁻¹) | Activation Energy E KJ·mol⁻¹ | Pre-exponential Factor F/(s⁻¹) | Heat of Reactions HJ·kg⁻¹ |
|-----------|------------------------|----------------------------------------|----------------------------------|----------------------------|-------------------------------|--------------------------|
| THL       | 1757                   | 0.39                                   | 1239                             | 1.760×10⁵                  | 1.660×10¹⁶                   | 1.363×10⁶                |
| PBXN-109  | 1663                   | 0.382                                  | 572.5                            | 1.373×10³                  | 1.995×10¹²                   | 0.7805×10⁶              |
Table 4. Comparison of experimental values and calculated values of explosive thermal ignition temperature and corresponding delay time.

| Explosive Type | Explosive Size and Quality | Heating Range / Explosive Diameter | Explosion Temperature (℃) | Delay Time (s) |
|----------------|---------------------------|-----------------------------------|---------------------------|----------------|
|                |                           | Measured Values                  | Average Value            | Calculated Value | Error (%) | Measured Values                  | Average Value | Calculated Value | Error (%) |
| TTH           | Φ5cm 65g                  | 1.2                                | 350                       | 366             | 3          | 358                       | 3            | 326             | 9          | 3          | 3          | 3.2         | 6.66 |
|               | Φ10cm 265g                | 0.6                                | 575                       | 491             | 4.8        | 533                       | 5.5          | 495             | 7          | 4.9        | 5.6        | 14.3 |
| PBXN-109      | Φ5cm 65g                  | 1.2                                | 304                       | 324             | 2.8        | 318                       | 2.9          | 290             | 8.8        | 3          | 3.3        | 10.0 |
|               | Φ10cm 265g                | 0.6                                | 365                       | 391             | 4.5        | 378                       | 4.5          | 336             | 11         | 4.5        | 4.8        | 6.25 |

It can be seen from the comparison between the experimental value and the calculated value of the thermal ignition temperature and the corresponding delay time in table 4 that: it adopts the shell explosive thermal ignition model based on the thermal imbalance theory to calculate the explosive thermal ignition explosion temperature, in error ≤ 11%; and calculate the thermal ignition delay time, in error < 15%. Therefore, under the fixed experiment (~ 100MPa) condition, the shell explosive thermal ignition model can be used to semi quantitatively predict the thermal ignition explosion temperature and delay time.

5. Conclusion
Under the experimental restraint condition in this research, the TNT RDX Al explosive and PBXN-109 explosives in fast heating action can cause thermal ignition, but the chemical reaction intensity is not consistent; Besides, the thermal ignition explosion temperature and delay time increase with the ratio of heating range to explosive size decrease, and both of them are larger than the 5s burst point.

It uses the shell explosive thermal ignition model based on thermal imbalance theory to calculate the explosive thermal ignition explosion temperature and delay. Because the Arrhenius reaction rate can not accurately reflect the chemical reaction kinetics process, the experimental value and the calculated value have errors, and there is an error between the experimental value and the calculated value. However, within a certain error range, the model can be used to semi quantitatively predict the explosion temperature and delay time.

References
[1] Evaluation Experiment of Nonnuclear Ammunition about Fatalness MIL-STD-2015C 2003
[2] Merzhanov A G and Abromov 1981 V A Propellants and Explosives 130-48
[3] Blaine W Asay 2009 Non-Shock Initiation of Explosives (New York)
[4] Feng Chang-gen 1988 Thermal Explosion Theory (Beijing: Science Press)
[5] Feng Chang-gen 1991 Thermal Ignition Theory (Ji Lin Science and Technology Press)
[6] Wang Li qiong, Feng Chang-gen and Du Zhi ming 2005 *Theory and Experiment about explosion and ignition in finite space* (Beijing : Beijing Institute of Technology Press)

[7] Jin Shao-hua and Song Quan-cai 2010 *Explosive Theory* (Xi’an: Northwest Polytechnical University Press)

[8] Performance Data Manual of High-energy Explosives Information Office of 903 Institute.

[9] Tan Zheng and Guo Guang-wen 1994 *Thermal Physical Property of Alloy Steel* (Beijing: Metallurgical Industry Press)