Preliminary Study on Steady-state Combustion Condition during Ammunition Destruction by High-energy Combustion Method

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Abstract. In order to avoid deflagration to detonation transition during the ammunition destruction by high-energy combustion method, the internal pressure of the shell can be controlled by the fused exhaust hole on the mine shell. In this paper, the equilibrium pressure equation for the steady state combustion of the internal explosive in the open-hole shell is derived by the model referring to the zero-dimensional interior ballistic calculation method under the combustion chamber model of the solid rocket engine. According to the size of fused exhaust hole measured by mine destruction experiment, the internal steady combustion equilibrium pressure for TNT charged mine is 0.69 MPa, which is far below the literatures reported deflagration to detonation transition pressure upper limit, the calculated results are in accordance with the experiment data.

1. Introduction

The high-energy burning destruction method is a novel non-explosive destruction technique. Compared with the commonly used explosive destruction method, this technique can effectively avoid the secondary harm effect caused by explosion. Its action principle can be express by two steps: first high temperature molten slag or flame caused by burning high-energy combustion agent quickly melt through ammunition metal shell, then molten slag or flame ignited internal loading explosive, make it burn up and destroyed. It is easy to appear deflagration to detonation transition when the explosive combust under the closed or partially closed condition, therefore, it is necessary to study the safe combustion control condition of explosive in high-energy combustion ammunition destruction.

2. Deflagration to detonation transition and its Influence factors

It is generally agreed that deflagration to detonation transition include several different stages of development, such as steady combustion (pulse combustion), detonation (LVD) at low speed, high speed of detonation (HVD). It is a complex process of physical, chemical, influenced by many factors, including environment, loading conditions (pressure, loading density, pore size, particle size, the strength of shell, system closure, etc.) and the chemical properties of the explosives (thermal decomposition kinetics, chemical energy release rate, gas production rate, burning rate, ignition point, etc.).

Price. D researched the DDT mechanism of double-base high-energy propellant (VLU) [3] and found that under the strong constraint condition, pressure mutations area for excitation detonation is very close to the detonation point; pressure mutations can induce detonation in a very short time. Chen
Lang conducted PBXC03 pressed explosive DDT experiments, and established the explosive DDT calculation model [1], the results show that under the weak constraint, gas leakage and pressure drop caused by tube damage are major restricting for deflagration to detonation transition. Therefore, the necessary condition for deflagration to detonation transition is the critical pressure in projectile. When the high-energy combustion method is used to destroy the ammunition, the gas produced by explosive combustion can be released through the melted through-hole on the ammunition shell, to avoid forming excessive pressure which causes DDT. Hence, the area of melted through-hole plays a decisive role in controlling the internal pressure of the projectile.

In this paper, the relationship between the melted through-hole area and the equilibrium pressure of the explosive in the projectile body is analyzed. The control conditions of "safe combustion" of explosives in this semi-closed system were preliminarily discussed and verified by mine destruction experiments.

3. Upper pressure limit of steady state combustion of explosive
The upper pressure limit of the explosive combustion is the highest pressure that the explosive can keep burning without detonation. For liquid, powdery and low density explosives, this value is relatively low. While for injection, high-density compression, especially the gelatinous explosive this value is relatively high. The measured upper pressure limit of steady state combustion of parts explosives under the same condition is listed in tab 1.

| explosive          | Upper pressure limit /MPa | Detonator     | Upper pressure limit /MPa |
|--------------------|---------------------------|---------------|---------------------------|
| Powdery PETN       | 2.5                       | Explosive colloid | >120                      |
| Powdery RDX        | 2.5                       | NC            | 2.0                       |
| Powdery TNT        | 6.5                       | AP compound   | 1.01~1.75                 |
| Powdery PA         | 6.5                       | Fulminate     | 1.0                       |
| Pressed PETN(ρ=1.65) | >21                        | Lead aside    | Explode in any pressure   |

4. Deduction of equilibrium pressure equation for steady state combustion of internal explosive in projectile with through-hole
Due to the complexity of DDT test and theoretical calculation, the simplified engineering model is adopted in this paper. Referring to the zero-dimensional interior ballistic calculation method under the combustion chamber model of the solid rocket engine, regardless of the flow parameters along the axial distribution, using average value, the complex flow field is simplified to zero dimension model. On the basis of this, the equilibrium pressure equation is derived for steady combustion of the internal explosive in projectile with through-hole.

4.1. Assumption condition
In order to calculate steady-state combustion pressure, the following basic assumptions must be followed:(1) the combustion products are complete gas, which should obey the complete gas state equation;(2) the combustion of the main explosive should obey the combustion rules; (3) the combustion product state of the shell should be uniformly distributed everywhere.

4.2. Equation deduction
Under the steady-state combustion condition, the gas formation rate of combustion reaction in projectile should be equal to the ejection rate of combustion products. According to this mass conservation condition, it can be expressed that:
\[
\frac{dm_r}{dt} = \dot{m}_b - \dot{m}_i \\
\dot{m}_b = \rho A_r \bar{r} \\
\dot{m}_i = \bar{p} V
\]

\(\rho\) — explosive density; \(A_b\) — explosive combustion area; \(m_r\) — the mass of combustion products in projectile; \(m_b\) — the mass of generated combustion products; \(m_t\) — the mass of ejected combustion products; \(\bar{p}\) — the average density of combustion products; \(V\) — the volume of combustion products.

By differential calculus, it can be derived by equation 3:

\[
\frac{dm_r}{dt} = \bar{p} \frac{dV}{dt} + V \frac{d\bar{p}}{dt}
\]  

(4)

It suggested that the mass change rate of the combustion products in projectile is made up by two parts. The \(\bar{p} \frac{dV}{dt}\) represents the mass of combustion products required to fill the volume generated by explosive combustion in the unit time, which can be expressed:

\[
\bar{p} \frac{dV}{dt} = \bar{p} A_b \bar{r}
\]

(5)

The \(V \frac{d\bar{p}}{dt}\) represents the gas mass required to change the gas density in the unit time.

According to ideal gas state equation \(\rho = \rho RT\), it can be derived that:

\[
\frac{V}{RT} \frac{d\bar{p}}{dt} = \frac{V}{RT} \frac{d\rho}{dt}
\]

(6)

Based on above, it can be derived that:

\[
\bar{p} \frac{dV}{dt} + V \frac{d\bar{p}}{dt} = \dot{m}_b - \dot{m}_i = \rho A_r \bar{r} - \dot{m}_i \iff \bar{p} A_r \bar{r} + V \frac{d\bar{p}}{dt} = \rho A_r \bar{r} - \dot{m}_i \iff \\
\frac{V}{RT} \frac{d\bar{p}}{dt} = A_r (\rho - \bar{p}) - \dot{m}_i
\]

(7)

Where, \(T\) is the temperature of the combustion product, which is the pressure inside the projectile.

The combustion rate of the explosive is consistent with the exponential combustion law:

\[
\bar{r} = a + b \bar{p}^n
\]

(8)

In a certain pressure range (about 0.0067MPa—20MPa), most of the explosives can be burned in steady state, and their combustion speeds are linear with pressures \(^6\), under the condition \(n=1\). In the actual combustion process, the density of the combustion products is much less than the density of the internal explosive, \(\bar{p} < (1\% - 2\%) \rho\), the equation 3-7 can be expressed simply as:

\[
\frac{V}{RT} \frac{d\bar{p}}{dt} = A_r (\rho - \bar{p}) - \dot{m}_i
\]

(9)

\(\dot{m}_i\) means the mass of ejected combustion products in unit time. The flow condition of the combustion products is observed from the open section, and the mass pass through cross section can be expressed as:

\[
\dot{m}_i = \rho_i U A
\]

(10)

Where, \(\rho_i\) — the average density of ejected combustion product gases; \(U\) — average velocity of particle motion; \(A\) — the area of the through-hole.

According to ideal gas state equation \(\rho = \rho RT\), it can be derived that:

\[
\dot{m}_i = \frac{P_0}{RT_0} U A
\]

(11)

Where, the \(P_0\) and \(T_0\) are the pressure and temperature of the exhaust gas, respectively.

The exhaust process of the gas in the shell can be regarded as the isentropic expansion process.
Referring to the pressure relationship before and after the sparse wave in gas dynamics, which can be expressed as:
\[
\begin{align*}
\rho_2 &= \rho_1 \left(1 + \frac{k-1}{2} \frac{u_2 - u_1}{c_1}\right)^{\frac{2}{k-1}} \\
T_2 &= T_1 \left(1 + \frac{k-1}{2} \frac{u_2 - u_1}{c_1}\right)^{\frac{2}{k}} \\
p_2 &= p_1 \left(1 + \frac{k-1}{2} \frac{u_2 - u_1}{c_1}\right)^{\frac{2}{k}}
\end{align*}
\] (12)

Where the subscript 1 denotes the pre-wave parameter and the subscript 2 denotes the post-wave parameter. The combustion products that pass through the sparse wave will expand to reach the same pressure as outside. The relationship between the velocity of the particle \(u\) and the pressure inside the shell can be obtained by the formula 12.
\[
u = \frac{2c}{k-1} \left[ \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} - 1 \right]
\] (13)

When the sparse wave acts on the stationary medium, the scattering velocity of the particle is opposite to the propagation direction of the sparse wave, so the value \(u\) in the equation is negative, than input its absolute value to equation 11, it can be obtained that:
\[
\dot{m}_i = \frac{p_2}{RT_0} A \cdot \frac{2c}{k-1} \left[ 1 - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right] \left(1 + \frac{k-1}{2} \frac{u}{c}\right)^{\frac{2}{k+1}}
\] (14)

According to the state parameters expression of pre-wave and post-wave, it can be obtained that:
\[
\frac{p_2}{T_0} = \frac{T}{T} \left(1 + \frac{k-1}{2} \frac{u}{c}\right)^{\frac{2}{k+1}}
\] (15)

Substitute it into equation 14, it can be obtained that:
\[
\dot{m}_i = \frac{\bar{P}}{RT} \cdot \frac{2c}{k-1} \left[ 1 - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right] \left(1 + \frac{k-1}{2} \frac{u}{c}\right)^{\frac{2}{k+1}}
\] (16)

Substitute expression between the particle velocity \(u\) and the pressure in the shell \(p\) into equation 16, it can be obtained that:
\[
\dot{m}_i = \frac{\bar{P}}{RT} \cdot \frac{2c}{k-1} \left[ 1 - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right] \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}
\] (17)

Substitute equation 9 into equation 17, it can be obtained that:
\[
\frac{V}{RT} \frac{dp}{dt} = A \cdot p (a + b p^n) - \frac{\bar{P}}{RT} \cdot \frac{2c}{k-1} \left[ 1 - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right] \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}
\] (18)

When the combustion is stable, the pressure inside the shell remains constant, \(\frac{dp}{dt} = 0\), it can be obtained that:
\[
A \cdot p (a + b p^n) = \frac{\bar{P}}{RT} \cdot \frac{2c}{k-1} \left[ 1 - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}} \right] \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}
\] (19)

This expression is the relationship between the equilibrium pressure \(p\) of the internal explosive and the area \(A\) of the shell combustion though-hole under the semi-closed condition.
5. Solve the equilibrium pressure of explosive steady combustion

Two high-energy combustion agents were charged under symmetrical settings, and the high-energy combustion destruction experiments were carried out on one certain type of anti-tank landmines. The actual dimensions of shell perforation hole in the case of mine safety combustion destruction are measured, as shown in fig. 1.

![Figure 1 the device for high-energy combustion destruction and mine shell perforation hole in the case of safety combustion destruction](image)

Charge of some type anti-tank mines is cylindrical injection TNT charge with 10 cm high, 30 cm diameter, its steady combustion obey geometric burning rules, after ignition through shell perforation hole, propellant combustion area can be considered to be a flat cylindrical cross-section area of landmines, the calculation should also remove the cross-sectional area of the fuse chamber. The area of the exhaust hole can be approximated as a round hole with a diameter of 3 cm according to the experimental results.

According to the gauss law, the heat \( Q \) released by TNT combustion reaction can be calculated. Without regard for the heat loss and assuming all heat emitted by TNT combustion was used to heat reaction products, the average specific heat capacity of the product can be calculated according to the composition of the product, and also the temperature \( T \) of reaction products can be obtained. Based on the combustion reaction equation of TNT, the average molar mass of the gas product can be calculated by complete gas state equation, and then the sonic \( c \). The parameters required to calculate the equilibrium pressure are shown in table 2.

| Parameter | Value     | Parameter | Value     | Parameter | Value    |
|-----------|-----------|-----------|-----------|-----------|----------|
| \( A_b \) | 300 cm\(^2\) | \( n \) | 1 | \( c \) | 12.19 cm/s |
| \( \rho \)  | 1.60 g/cm\(^3\) | \( R \) | 8.314 J/(mol•K) | \( k \) | 1.4 |
| \( a \)     | 0.009 cm/s | \( T \) | 3151 K | \( p_0 \) | 0.1 MPa |
| \( b \)     | 0.005 cm/(s•MPa) | \( Q \) | 227.9 kcal/mol | \( A \) | 7.065 cm\(^2\) |

Substituted the parameters into the equation 21, the steady combustion equilibrium pressure of TNT explosive inside the mine shell with open-hole was calculated to be 0.69 MPa. Equilibrium pressure is critical to maintain steady combustion, when pressure is higher than this value, the combustion of explosives will tend to be unstable, but still far from deflagration to detonation transition pressure upper limit, and therefore, the calculated equilibrium pressure value should be lower than actual measured TNT deflagration to detonation transition pressure upper limit as shown in table 2.

6. Conclusions

In order to avoid deflagration to detonation transition during the ammunition destruction by high-energy combustion method, the fused exhaust hole on the shell plays an important role to control the
internal pressure inside the mine shell. The equilibrium pressure equation for the steady state combustion of the internal explosive in the open-hole projectile is derived by the simplified model referring to the zero-dimensional interior ballistic calculation method under the combustion chamber model of the solid rocket engine. According to the size of fused exhaust hole measured by mine destruction experiment, the internal steady combustion equilibrium pressure for TNT charged mine is 0.69 MPa, which is far below the literatures reported pressure limit for deflagration to detonation transition, the calculated results are in accordance with the experiment. However, this simplified model ignores complex multiphase flow field parameters, it is only approximated result. The work of this paper can provide a new idea for the theoretical study of the safety control for ammunition destruction by high-energy combustion method.

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