Calculation and Analysis of Interior Ballistic Performance of Propellant Containing Ionized Seeds

Chunlin Chen *, Baoquan Mao, Xianghua Bai, Qijin Zhao

Army Armored Forces Academy, Beijing, China
* Corresponding author: Chunlin Chen

Abstract: Ionization seed refers to a compound composed of alkali metal elements with low ionization potential. Because of its lower ionization potential, it is easier to decompose and ionize in the propellant gas to generate plasma with conductive characteristics. Its gas is easier to form a sheath under the action of a magnetic field, which inhibits the forced heat transfer of high-temperature gas, but the addition of ionized seeds will change the original properties of the propellant. Therefore, this paper mainly uses a combination of theoretical research, simulation analysis and experimental verification to study the impact of ionized seeds on the internal ballistic performance of the propellant. The results showed that the same content of different types of ionized seeds, the difference in pressure test data is small. When 6% cesium nitrate ionized seeds were added to the propellant, the chamber pressure and initial velocity were reduced by 1.87% and 0.94%, respectively. The addition of ionized seeds had a certain impact on the internal ballistic performance.

Keywords: ionized seeds; interior ballistic; numerical simulation

1. Introduction

In the process of internal ballistics, the propellant containing ionized seeds burns to generate a plasma with conductive properties [1-2]. The gas is easier to form a sheath under the action of a magnetic field, which can inhibit the forced heat transfer of high-temperature gas, but the addition of ionized seeds will change the original propellant [3]. It is of nature and may affect the ballistic performance of the barrel. To study the impact of ionized seeds on the internal ballistic performance of the propellant. Through theoretical calculation of the important internal ballistic parameters of different types and different contents of ionized seed propellant, the initial parameters of the internal ballistic model are determined, and the internal ballistic model is constructed to simulate the influence of changes in internal ballistic performance such as chamber pressure in the combustion process.

2. Modeling

2.1. Calculation of Key Parameters of Interior Ballistics

2.1.1. Gunpowder power calculation

Gunpowder power is one of the important parameters in the calculation of weapon internal ballistics, which represents the work done by the combustion of 1000g propellant under constant volume conditions. When the propellant is burned in a closed explosive, the gas will increase its density under the action of pressure. The van der Waals equation can be used to express the real gas state and combined with the Nobel-Abel equation, the gunpowder force can be simplified as:

$$f = nRT \tag{1}$$

2.1.2. Covolume calculation

The density of the high-pressure gas generated at the moment the propellant burns is very high. The volume occupied by the gas molecules themselves cannot be ignored.

$$\alpha = 0.001 V_1 \tag{2}$$

The covolume represents the volume occupied by the combustion product of 1kg propellant gas under standard conditions. The gas combustion product can be obtained according to the solution, and the covolume can be obtained.

2.1.3. Burning rate coefficient calculation

In order to study the effect of burning speed on interior ballistic performance, it is first necessary to determine the burning speed equation and establish a propellant combustion model. The burning rate equation constructed with the burning rate coefficient, burning rate index, pressure and other parameters of the propellant combined with the shape equation, internal ballistic equation and other internal ballistic equations, so that it is easier to reflect the impact of internal ballistic performance. Therefore, the burning rate can be expressed by the following formula (3):

$$u(p) = u_1 p \tag{3}$$

In the formula, $u(p)$ is the burning rate, and u_1 is the burning rate coefficient.

It is more convenient to use theory to calculate the burning rate coefficient of different types and contents of ionized seed propellant. To calculate the burning rate coefficient, the burning rate equation must be constructed first. Analysis from the perspective of chemical changes in the combustion of propellant components. When the propellant burns, the main components in the condensed phase reaction zone are first decomposed into some NO_2 gas. Studying the mechanism and reaction speed of NO_2 reduction reaction is a necessary condition for establishing the propellant combustion formula [4].

In the initial stage of combustion, the propellant are all chemical groups, so the chemical formula of each component of the propellant can be represented by the corresponding group. If the propellant component is represented by C_i:

$$(CO)_{B_{i1}}(CH_2)_{B_{i2}}(CHO)_{B_{i3}}(CH_2O)_{B_{i4}}(NO_2)_{B_{i5}} \quad (4)$$

In the formula, B_{ij} is expressed as the amount of the substance of the corresponding group j contained in 1kg of the propellant component C_i, expressed by the vector B_i as:

$$B_i = (B_{i1}B_{i2}B_{i3}B_{i4}B_{i5}) \quad (5)$$

Taking function $\eta(p)$ as the equation expressing the degree of cracking of $[CHO]$,the amount of gas produced by the decomposition of 1kg of propellant component C_i during the combustion process is:

$$N_{ij}(p) = \sum_{\substack{j=1 \\ j\neq 3}}^{5} B_{ij} + \eta(p)B_{i3} \quad (6)$$

$\eta(p)$ is expressed as a function related to pressure, which can be expressed as:

$$\eta(p) = 2 - \exp(0.6931(1 - p/p^*)) \quad (7)$$

p is the total pressure of the gas phase, and p^* is the specific pressure.

From equations (6) and (7), the amount of NO_2 produced during the combustion process of the propellant can be expressed, which is represented by $\theta(p)$:

$$\theta_0(p) = B_5 / N(p) \quad (8)$$

$$N(p) = \sum_{\substack{j=1 \\ j\neq 3}}^{5} B_j + \eta(p)B_3 \quad (9)$$

$$\alpha = B_1/B_5; \beta = B_2/B_5; q = B_3/B_5; r = B_4/B_5$$

$$\theta_0(p) = 1/(\alpha + \beta + \eta(p)q + r + 1) \quad (10)$$

Suppose the propellant formula is:

$$C_i = (c_1 c_2 \cdots c_i) \quad (11)$$

$$\sum_{i=1} c_i = 1 \quad (12)$$

The density of the propellant is:

$$\rho_p = (\sum_{i=1}(c_i/\rho_i))^{-1} \quad (13)$$

ρ_i is the density of propellant component C_i

It can be determined that the burning rate of the propellant (initial temperature 20 ℃) is:

$$u(p) = 16.76 \times (p/p^*) \times \theta_0^2(p)/\rho_p \quad (14)$$

The available burning rate coefficient is:

$$u_1 = 16.76 \times \theta_0^2(p)/p^*\rho_p \quad (15)$$

After theoretical calculation, the parameters such as gunpowder power, covolume and burning rate coefficient of ionized seed propellant with different contents of cesium nitrate, potassium nitrate and sodium nitrate are obtained, as shown in the Figure 1-3.

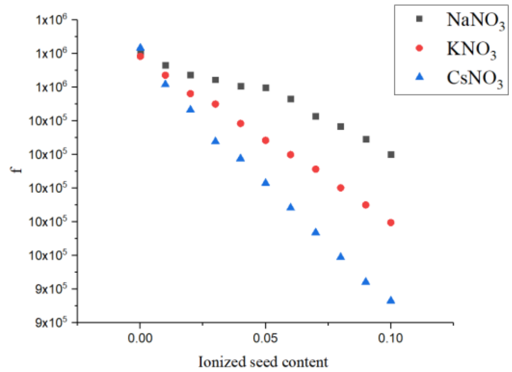

Figure 1. The relationship between gunpowder power and ionized seed content

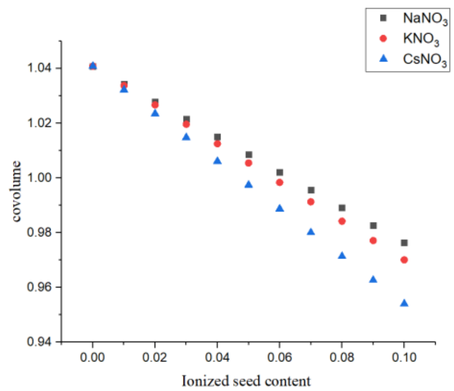

Figure 2. The relationship between covolume and ionized seed content

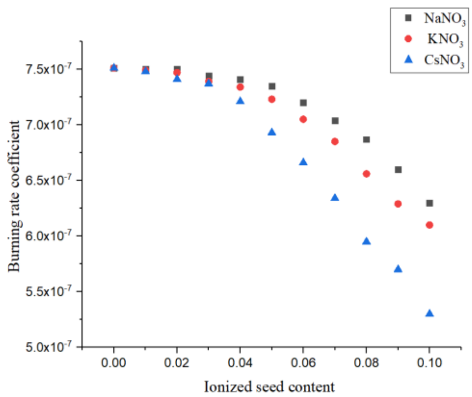

Figure 3. The burning rate index changes with the content of ionized seeds

2.2. Build an Interior Ballistic Model

The interior ballistic equations composed of shape equation, burning rate equation, motion equation, etc. are analyzed through key internal ballistic parameters such as gunpowder power, covolume and burning rate coefficient [5].

$$\begin{cases} \psi = \chi Z(1+\lambda Z+\mu Z^2) \\ \dfrac{dZ}{dt} = \dfrac{u_1 p}{e_1} \\ Sp = \varphi m \dfrac{dv}{dt} \\ Sp(l+l_\psi) = f\omega\psi - \dfrac{\theta}{2}\varphi m v^2 \\ v = \dfrac{dl}{dt} \end{cases} \tag{16}$$

The equations are iteratively calculated to simulate the changes in the pressure of the tube wall and the initial velocity of the projectile to analyze the impact on the internal ballistic performance.

3. Numerical Simulation

3.1. The Influence of Different Types of Ionized Seeds on Chamber Pressure and Initial Velocity

Take 2%, 6% and 10% cesium nitrate, potassium nitrate and sodium nitrate ionized seed propellant respectively, and carry out numerical simulation according to the internal ballistic parameters of a certain type of artillery. The calculation results are shown in Figure 4 to Figure 6.

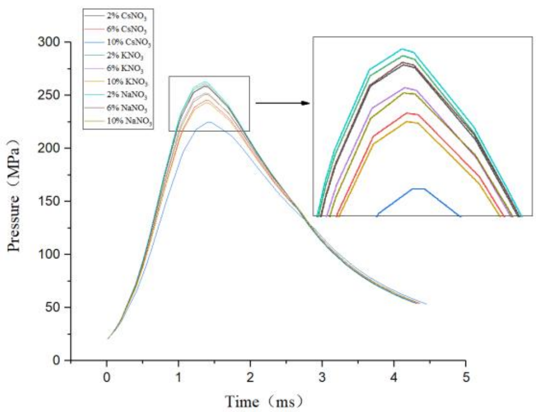

Figure 4. The influence of different types of ionized seed propellant on chamber pressure.

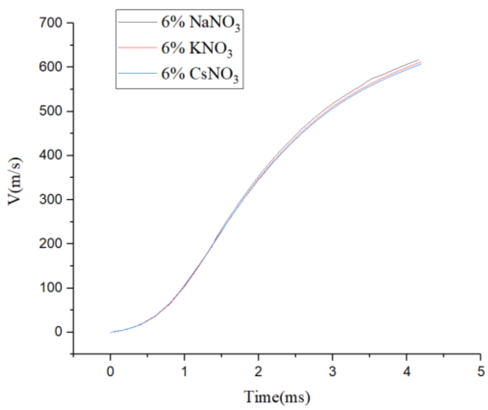

Figure 5. The effect of 6% ionized seed propellant on the muzzle velocity of the projectile.

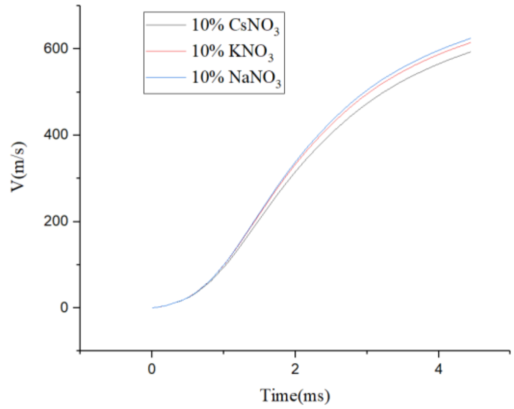

Figure 6. The effect of 10% ionized seed propellant on the muzzle velocity of the projectile

From Figure 4 to Figure 6, it can be seen that adding different types of ionized seeds has a certain impact on the gun chamber pressure. When keeping the total mass of the propellant and the content of ionized seeds unchanged, it is compared with ionized seeds of sodium nitrate and potassium nitrate. Cesium nitrate ionized seeds have the greatest impact on the chamber pressure of the artillery, and the chamber pressure data changes more. Sodium nitrate ionized seeds have the least impact on the chamber pressure of the artillery. At the maximum chamber pressure, the chamber pressure when the 10% sodium nitrate ionized seed propellant burns is approximately 245 MPa, which is about 21 MPa and 30 m/s higher than the chamber pressure and the initial velocity of the projectile when the 10% cesium nitrate ionized seed propellant burns. The chamber pressure and muzzle velocity of the% sodium nitrate ionized seed propellant during combustion are about 6 MPa and 7 m/s higher than that of the 6% cesium nitrate ionized seed propellant. The ionized seed content is 6%, which basically does not affect the internal ballistic performance. When the ionized seed content reaches 2%, the simulation results show that there is little change in the initial velocity of the projectile. When the ionized seed content reaches 10%, the impact of the propellant on the chamber pressure and projectile velocity is obvious.

3.2. The Influence of Different Content of Ionized Seeds on Chamber Pressure and Initial Velocity

The addition of cesium nitrate ionized seed propellant has a significant effect on chamber pressure. Therefore, the internal ballistic characteristic parameters of the different content of cesium nitrate propellant obtained by theoretical calculation are substituted into the model for simulation calculation, and the influence of the change of ionized seed content on the internal ballistic performance is numerically simulated. The calculation results are shown in Figure 7 to Figure 8.

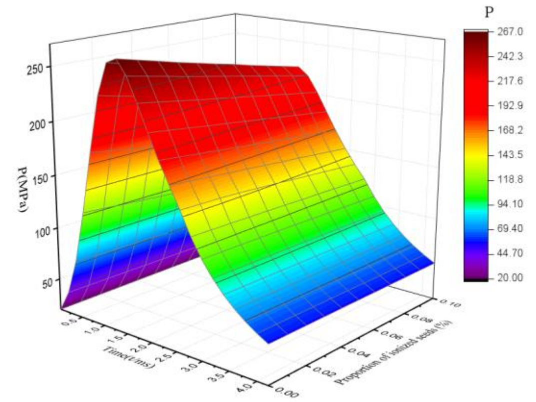

Figure 7. The effect of 6% cesium nitrate ionized seeds on chamber pressure

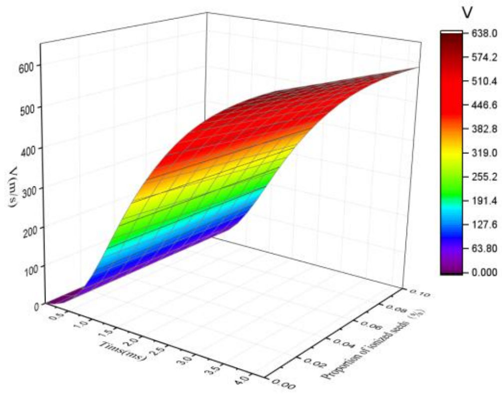

Figure 8. The effect of 6% cesium nitrate ionized seeds on initial velocity

The increase in ionized seed content will reduce the chamber pressure and initial velocity in the barrel. Among them, the highest chamber pressure and the initial velocity of the projectile when burning with 6% cesium nitrate ionized seed propellant are reduced by about 7MPa and 9m/s compared with the ionized seed without adding cesium nitrate, the chamber pressure is reduced by 3.37%, and the initial velocity is reduced by 1.41%. Without changing the total mass of the propellant, the addition of ionized seeds will reduce the quality of the original components of the propellant. The heat released during combustion in the chamber and the work done to the outside will also decrease as the ionized seeds increase, thereby reducing the chamber pressure. And muzzle velocity. It can be seen that, compared with the propellant without ionized seeds, the highest chamber pressure is reduced by 3.37%, and the initial velocity of the projectile is reduced by 1.41%, which has little effect on the internal ballistic performance.

4. Test Verification

4.1. Experimental Composition

In order to simulate the real scene of propellant burning in the pipe wall, the gas pressure and temperature are as close as possible to the real chamber pressure and explosive temperature of the propellant. The propellant gas generating device adopts a closed reactor and uses an ignition powder package for ignition. The pressure test system is mainly composed of a pressure sensor and a pressure data acquisition system installed at the top of the closed reactor. As shown in Figure 9

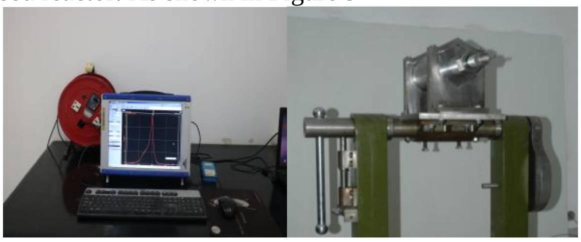

Figure 9. Closed reactor

4.2. Experimental Result

In the experimental verification of this article, a total of 10 sets of experiments were carried out, and the pressure time data of the propellant gas under different types, different contents of ionized seeds and different filling densities were obtained by collecting the pressure data collected in the pressure test system. Three groups of ionized seeds with the same content and different types were carried out, and 14.5g of cesium nitrate, potassium nitrate and sodium nitrate propellants each with a mass fraction of ionized seeds of 5% were prepared. A total of three groups of cesium nitrate-containing propellants were carried out, and 14.5g of 2%, 6%, and 10% cesium nitrate propellants were produced respectively. Three sets of ionized seed propellants of the same content, type, and different filling density were carried out. Three sets of ionized seed propellants with a mass fraction of 6% cesium nitrate were prepared, and 14.5g were tested and verified in airtight explosives with different combustion chambers.

Through the closed explosive test, the relationship between pressure and time data is obtained. The pressure and time data obtained with 2% ionized seeds and no ionized seeds are basically consistent, as shown in Figure 10.

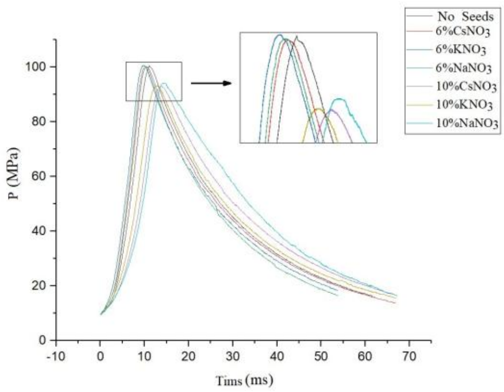

Figure 10. The effect of ionized seeds on pressure

It can be seen from Figure 10 that the pressure test data of the same content of different types of ionized seeds are not much different, and it can be seen that the type of ionized seeds does not affect the internal ballistic performance. When the ionized seed content is 6%, the pressure test data is closer to the data obtained without adding ionized seeds, which will have a certain impact on the internal ballistic performance.

5. Conclusion

With the increase of the ionized seed content, when the ionized seed content exceeds 10%, the ionized seed will have a greater impact on the combustion performance and internal ballistic performance of the propellant. When 6% cesium nitrate ionized seeds were added to the propellant, the chamber pressure and initial velocity were reduced by 1.87% and 0.94%, respectively. The addition of ionized seeds has a certain impact on the internal ballistic performance.

References

[1] Wang D. Research on Dynamic Simulation Test Technology of Artillery Recoil. North University of China, 2020.

[2] Li C, Mao B Q, et al. Research on the Thermal Insulation Characteristics of Plasma in the Gun Barrel under Magnetic Confinement. Journal of Artillery Launching and Control, 2018, 39 (03): 6-10.

[3] Zhao K, Lu Y J, Li F, et al. Experimental investigation on the effect of ionization seed mass fraction on gas plasma jet deflection. 2020, 171: 257-264.

[4] Li Z T, Gunpowder and interior ballistics. Beijing: National Defense Industry Press, 2001.

[5] Zhang X B, Gun interior ballistics. Beijing: Beijing Institute of Technology Press, 2014.