

Numerical simulation research of inner ballistic overload of guided projectile based on coated mixed charge

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Abstract. In order to study the numerical variation law of the internal ballistic overload of the guided projectile under different coated mixed charge structures, and to provide a basis for the development of a new type of high muzzle velocity and low overload propellant charge design, taking a large-caliber suppressed artillery as the simulation object, the layered combustion model of the coated propellant was established by using the one-dimensional two-phase flow theory, and the lace 37-hole nitroguanidine propellant was used as the main charge (MC) and lace 19-hole nitroguanidine coated propellant as auxiliary charge (B). The effects of mixed charges with different charge mass, different mixing ratios and different coating layer thicknesses on the internal ballistic overload value were studied by simulation calculation. The research results show that the increase of the total charge mass will increase the overload impact of the guided projectile and the muzzle velocity of the projectile ; with the increase of the thickness of the coating layer and the proportion of the coated propellant in the mixed charge ratios, the longitudinal overload and the muzzle velocity of the projectile in the chamber of the guided projectile will be decreased to a certain extent and the time point when the maximum overload occurs will be delayed; under the structure of the coated mixed charge, the influence of the proportion of coated propellant in different mixed charge ratios and the coating layer thickness of coated propellant on the launch overload of the guided projectile is greater than the muzzle velocity of the projectile, and the effect of reducing the firing overload in the chamber by increasing the proportion of coated propellant in different mixed charge ratios is the most significant.

Keywords: Coated mixed charge, Guided projectile, Launch overload, In-chamber combustion, Numerical simulation.

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1 Introduction

With the rapid development of science and technology, high and new technologies such as microelectronics, sensors, navigation, and intelligent identification are widely used in the design of ammunition. Guided projectiles are a kind of smart ammunition that is fired by artillery and precisely controlled and attacked by its own guidance device. The guidance and control system is applied to conventional weapons and ammunition, so that conventional weapons have high precision, and artillery has stronger tactical flexibility and battlefield deterrence^[1-2]. However, there are many technical difficulties in the development and design of the matching propellant charge at present, such as the combustion of the propellant charge and the high-speed movement of the projectile in the chamber, the guidance and control system of the guided projectile will be in a high overload environment, and the precision components in it will be easily damaged by high acceleration shocks. In fact, the projectile may be subjected to an acceleration exceeding 10,000 g during the launch process. During the period, accompanied by violent collision and high-speed rotation, the control device of the guided projectile is easily damaged in this harsh environment, which will cause the launch failure or even premature explosion in the projectile chamber and cause casualties^[3]. Therefore, in order to avoid such a situation, it is very important to study the relationship between the combustion in the chamber of the guided artillery charge and the launch overload, so as to further optimize and improve the design of the guided artillery charge.

At present, relevant scholars at home and abroad mainly analyze and study the overload situation in the artillery chamber for the projectile itself. However, from the perspective of propellant charge, there are very few studies on the combustion process in the propellant charge chamber and the mechanism of firing overload. In this paper, a large-caliber suppressed artillery gun was taken as the simulation object, and the layered combustion model of the coated propellant was introduced for the structure of the coated mixed charge. In addition, the one-dimensional two-phase flow theory was used. The lace 37-hole nitroguanidine propellant was selected as the main charge (MC) and the lace 19-hole nitroguanidine coated propellant was selected as the auxiliary charge (B). The effects of different charge mass, different mixing ratios and different coating thicknesses on the internal ballistic overload value were studied by simulation calculation to provide technical support for the design of a new type of high muzzle velocity and low overload propellant charge.

2 Establishment of mathematical theoretical models

Due to the characteristics of high pressure and high loading density in the chamber of large-caliber suppressed artillery, the problem of projectile launch overload in the chamber is particularly prominent, especially the real-time monitoring and precise control of parameters such as the launch overload in the chamber are still difficult^[4]. The study of overload in the firing chamber of artillery has always been a difficult problem for scholars at home and abroad^[5]. At present, the projectile overload value in the artillery chamber is mainly tested and studied by the built-in acceleration sensor. This method is extremely expensive due to the difficulty in recovering the high-speed projectile and the acceleration sensor is easily damaged during the test process^[6]. Therefore, in order to avoid a large number of ballistic tests, reduce the experimental workload and save resources such as manpower and financial resources, numerical simulation methods can be used for research. The one-dimensional two-phase flow simulation of the internal ballistic process of the artillery can accurately obtain the pressure value of the gunpowder gas that drives the projectile to launch in the chamber. Because the projectile movement process in the bore

and the calculation process of the firing overload in the bore are extremely complicated, in order to facilitate the calculation and simplify the process, this paper only considers the calculation of the longitudinal firing overload in the projectile bore. On this basis, combined with the classical internal ballistic theory, the overload numerical conversion is carried out according to the gunpowder gas pressure calculated by the one-dimensional two-phase flow theoretical model, so as to establish the theoretical model of the guided projectile internal ballistic launch overload.

2.1 Basic assumptions

According to the characteristics of the coated propellant burning in the chamber, basic assumptions are put forward as follows:

- The solid phase composed of gunpowder particles is continuously distributed in the gas phase, and the gunpowder particle group is treated as a pseudo-fluid with the characteristics of a continuous medium.
- The entire flow in the bore, including the flow in the ignition tube, is a one-dimensional unsteady flow, and all flow parameters are functions of coordinate x and time t .
- The composition of the combustion products of the gunpowder remains unchanged, and the thermodynamic parameters of the gunpowder gas, such as the gunpowder power, residual volume and specific heat ratio, remain constant.
- Both the main charge and the coated charge obey the geometric combustion law and the exponential combustion law.
- The shape, size and performance of the main charge and the coated gunpowder particles are strictly consistent, and the thickness of the coating layer is uniform.
- The moment when the gunpowder coating burns out and the base starts burning is continuous.

2.2 Mathematical model

2.2.1 One-dimensional two-phase flow fundamental conservation equations

Based on the above assumptions and according to the components of the artillery charge, the mathematical correction model is established as follows^[7]:

- Modified equation of gas phase mass conservation for coated mixed charge

$$\frac{\partial}{\partial t}(\phi \rho_g A) + \frac{\partial}{\partial x}(\phi \rho_g u_g A) = \sum_i \dot{m}_i A + \dot{m}_{ign} A + \dot{m}_k A + \dot{m}_g A \quad (1)$$

A is the barrel cross-sectional area, ϕ is the gas-phase porosity, ρ_g is the gas density, u_g is the gas velocity, $i=1, 2$ respectively represent the gas generation volume of main charge and coated propellant per unit volume, \dot{m}_{ign} is bottom igniter pack gas flow, \dot{m}_g is the gas flow rate of the ignition powder injected into the main charge bed per unit volume by the fire-passing hole, \dot{m}_k is gas generation rate of combustible components.

- Modified equation of solid phase mass conservation for coated mixed charge

$$\frac{\partial}{\partial t}(\phi \rho_i A) + \frac{\partial}{\partial x}(\phi \rho_i u_i A) = -\dot{m}_i A \quad (2)$$

- Gas-phase momentum conservation equation for coated mixed charge

$$\frac{\partial}{\partial t}(\phi \rho_g u_g A) + \frac{\partial}{\partial x}(\phi \rho_g u_g^2 A) + A \phi \frac{\partial p}{\partial x} = -\sum_i f_{s,i} A + \sum_i \dot{m}_i u_i A + \dot{m}_{ign} u_{ign} A + \dot{m}_k u_k A + \dot{m}_g u_g A \quad (3)$$

$f_{s,i}$ is interphase resistance.

- Modified equation of momentum conservation of solid phase for coated mixed charge

$$\frac{\partial}{\partial t}[\phi \rho_i u_i A] + \frac{\partial}{\partial x}[\phi \rho_i u_i^2 A] + \phi A \frac{\partial p}{\partial x} + A \frac{\partial(\phi R_i)}{\partial x} = f_{s,i} A - \dot{m}_i u_i A \quad (4)$$

R_i is the stress between the i-th gunpowder particles.

- Modified equation of gas-phase energy conservation for coated mixed charge

$$\frac{\partial}{\partial t}[\phi \rho_g A(e_g + \frac{u_g^2}{2})] + \frac{\partial}{\partial x}[\phi \rho_g u_g A(e_g + \frac{p}{\rho_g} + \frac{u_g^2}{2})] + p \frac{\partial \phi A}{\partial t} = \sum_i \dot{m}_i A \left(e_i + \frac{p}{\rho_i} + \frac{u_i^2}{2} \right) + \dot{m}_g H_g A + \dot{m}_k H_k A + \dot{m}_{ign} H_{ign} A - \sum_i f_{s,i} u_i A - \sum_i \bar{A}_{p_i} q_i A \quad (5)$$

e_i is the potential of the i-th granular propellant, H_k is combustible components generate gas stagnation enthalpy, q_i is heat exchange between the i-th granular propellant and the gas phase, \bar{A}_{p_i} is the particle surface area per unit volume of the i-th granular propellant.

2.2.2. Auxiliary equations

- The combustion rate equation of the coating layer propellant for coated mixed charge

$$\frac{de_b}{dt} = u_b p^n \quad (6)$$

- The combustion rate equation of the main charge and the base layer propellant

$$\frac{de_1}{dt} = u_1 p^n \quad (7)$$

- Shape function equations of the coating layer propellant for coated mixed charge

$$\begin{cases} \psi_2 = B \left(1 + \frac{e_1}{\Delta e_b} Z \right) \\ \sigma_2 = 1 \\ z = \frac{e - \Delta e_b}{e_1} \end{cases} \quad -\frac{\Delta e_b}{e_1} \leq Z \leq 0 \quad (8)$$

- Shape function equations of the main charge and the base layer propellant

$$\begin{cases} \psi_1 = \chi_1 Z_1 (1 + \lambda_1 Z_1 + \mu Z_1^2) \\ \sigma_1 = 1 + 2\lambda z + 3\mu z^2 \end{cases} \quad 0 < Z \leq 1 \quad (9)$$

$$\begin{cases} \psi_1 = \chi_s \xi (1 + \lambda_s \xi_s) \\ \sigma_1 = 1 + 2\lambda_s \xi \end{cases} \quad Z > 1 \quad (10)$$

χ_1 、 λ_1 、 μ 、 χ_s 、 λ_s 、 χ_2 、 λ_2 are shape function, which can be calculated.

In addition to the above-mentioned propellant burning rate and propellant shape function, the auxiliary equations also include interphase resistance, interphase heat exchange, equation of state, interparticle stress and the equation of propellant surface temperature^[8].

2.2.3 Basic equation of longitudinal overload in projectile bore

According to the classical internal ballistic theory, we have

$$a = \frac{Sp_d}{\varphi_1 m} = \frac{Sp_t}{\varphi_1 m(1 + \omega / 3\varphi_1)} \quad (11)$$

S is barrel cross-sectional area, P_t is bottom pressure of the chamber, P_d is bottom pressure of the projectile, ω is charge mass, φ_1 is resistance coefficient, m is projectile mass.

In order to facilitate the calculation, the gas pressure of the gunpowder in the chamber obtained by fitting the above one-dimensional two-phase flow theoretical model can be introduced into the longitudinal overload equation in the projectile chamber according to the charging conditions, and then the longitudinal overload curve in the projectile chamber can be obtained. Because the actual launch process of the guided projectile in the chamber is driven by the bottom pressure of the projectile to push the projectile forward, and the bottom pressure of the projectile can more truly reflect the force at the bottom of the projectile than the bottom pressure of the chamber. Therefore, in order to make the simulated launch overload value closer to the actual value, the projectile bottom pressure of the propellant charge is introduced into the equation for overload conversion in this paper, so as to calculate the internal ballistic launch overload value more accurately^[9]. In the set charging conditions, ensuring that the projectile does not exceed the maximum overload that can be tolerated and maintaining a certain high muzzle velocity and high power are the goals pursued by the charging workers.

2.3 Experimental verification of the theoretical model

When the mixed charge with the charge structure of 27/37H+23/19HB₁₁ (MC:B=7:3) is selected, the shooting test is carried out in the external field. The $p-t$ curve is measured by the piezoelectric pressure measuring system, and the projectile muzzle velocity is measured by the coil target. In the simulation, the structural parameters and loading parameters of the gun that are consistent with the field test are used for calculation, and then the simulated overload curve in the bore can be obtained. Comparing the simulated overload curve with the measured overload curve, the results are shown in Table 1 and Figure 1.

Table 1. Field test results and simulation results.

	a_m/g	$v_0/m \cdot s^{-1}$
Measured value	16910.46	1003.30
Analog value	17729.72	1091.33
Error	4.84%	8.77%

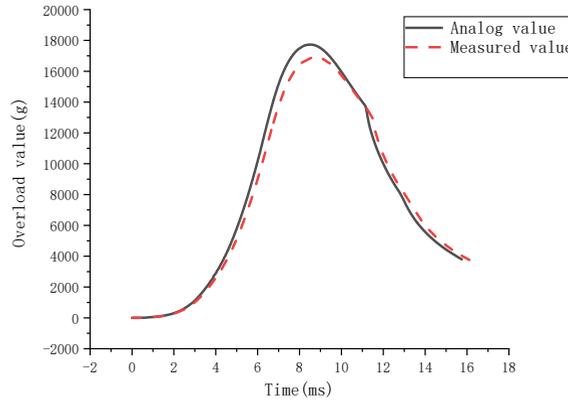


Fig. 1. Comparison between the test overload curve of artillery and the simulation overload curve.

From the data in Table 1, it can be seen that the error between the simulation calculation results and the test results is within 9%, and it can be seen from Figure 1 that in the longitudinal overload curve in the bore obtained by the two fittings, both the curve shape and the change trend are relatively approximative. Therefore, the model can be used to simulate the numerical change process of the internal ballistic launch overload under the coated mixed charge structure.

3 Results and discussion

3.1 Influence of mixed charges with different charge mass on internal ballistic overload values

Under the condition that the coated mixed charge structure is 27/37H+23/19HB₁₁ (MC:B=7:3), the coating layer thickness of coated propellant is 11%, and other parameters remain unchanged, only by changing the total charge mass and based on the above mathematical correction model, the overload numerical simulation of the internal ballistic process of a large-caliber suppressed artillery is carried out. The corresponding projectile muzzle velocity, maximum overload and overload curves are calculated as shown in Table 2, Figure 2 and Figure 3 .

Table 2. Influence of charge mass on internal ballistic overload value.

Total charge mass /kg	At the point of maximum overload /ms	Maximum overload /g	Projectile muzzle velocity /m·s ⁻¹
18.20	8.57	17729.72	1091.33
18.40	8.34	18413.55	1103.09
18.60	8.23	18991.80	1113.16
18.80	8.10	19599.70	1123.38

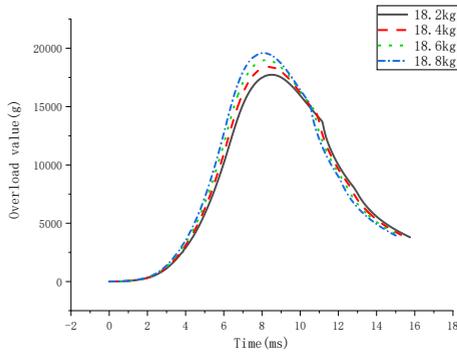


Fig. 2. $a-t$ curves under different total charge mass.

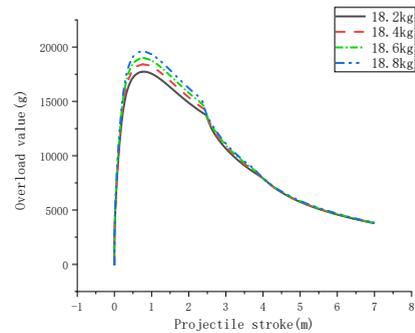


Fig. 3. $a-l$ curves under different total charge mass.

It can be seen from Figure 2 that the four $a-t$ curves from small to large charge mass have an obvious bump near 11.14ms, 11.04ms, 10.86ms, and 10.62ms, respectively. This is caused by the splitting of the main charge at this moment during the combustion process of the mixed charge of the main charge and the auxiliary charge. It can be seen from Table 2 and Figure 2 that with the increase of the total charge mass, the maximum longitudinal overload in the guided projectile and the muzzle velocity of the projectile gradually increase, and the maximum overload value is more significantly affected by the total charge mass than the projectile muzzle velocity. The time point of reaching the maximum overload is gradually advancing. It can also be seen from Figure 3 that as the total charge mass increases, the area integrated by the launch overload and projectile stroke curve in the guided projectile also be larger. This is because the increase in the total charge will inevitably lead to an increase in the total energy of the propellant, which further increases the gas pressure of the gunpowder in the chamber. Therefore, the requirements of the overload and muzzle velocity that the guided projectile can withstand can be met by properly adjusting total charge mass of the propellant charge.

3.2 Influence of mixed charges with different mixing ratios on internal ballistic overload values

The mixed charge loading structure is different from the single standard loading structure. The mixed charge under different mixing ratios affects the generation rate of the gunpowder gas, which in turn affects the overload of the inner ballistic of the guided projectile and the safety of the artillery launch. Therefore, the effect of mixed charges on internal ballistic overload under different charge mixing ratios can be studied by the control variable method. Under the premise that the total charge mass is 18.20kg, the coating layer thickness is 11% and other parameters are not changed, only by changing the mixed charge ratio, numerical simulation of internal ballistic overload of guided projectiles is carried out. The corresponding projectile muzzle velocity, maximum overload and overload curves are calculated as shown in Table 3, Figure 4 and Figure 5 .

Table 3. Influence of mixing ratio on internal ballistic overload value.

Mixing ratio (MC:B)	At the point of maximum overload/ms	Maximum overload/g	Projectile muzzle velocity/ $m \cdot s^{-1}$
8:2	8.20	18583.96	1103.07
7:3	8.57	17729.72	1091.33
6:4	8.90	17107.69	1082.25

5:5	9.35	16337.75	1070.84
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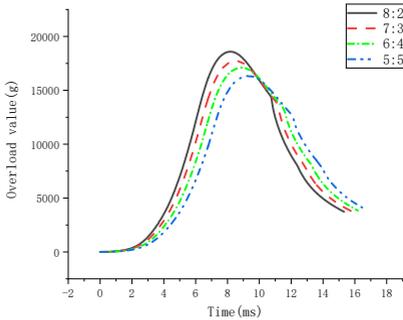


Fig. 4. *a-t* curves of different mixing ratios of main charge and coating charge.

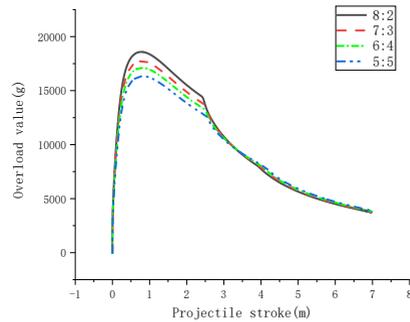


Fig. 5. *a-l* curves of different mixing ratios of main charge and coating charge.

It can be seen from Table 3, Figure 4 and Figure 5 that with the increase of the proportion of the coated propellant in the mixed charge ratios, the time for the firing overload in the chamber to reach the maximum value is delayed accordingly; the maximum overload value decreases; the muzzle velocity of the projectile also decreases slightly. When the ratio of the mass of the coated propellant to the total charge mass is changed from 20% to 50%, the internal ballistic launch overload value decreased by 12.09%, and the muzzle velocity of the projectile also decreased by 2.92%. In addition, the firing overload-time curves in the bore with different mixed charge ratios will also shift to the right as a whole with the increase of the proportion of the coated propellant. This is due to the addition of flame retardant materials to the outer layer of the coated propellant, which promotes the delayed combustion of the coated propellant, reduces the initial combustion rate of the charge combustion, and delays the generation of the maximum overload in the projectile chamber, and the pressure in the chamber also produces a platform effect. The energy utilization rate of the propellant can be improved.

3.3 Influence of mixed charges with different coating thicknesses on internal ballistic overload values

Since a kind of flame-retardant and insensitive material TOX is added to the outer layer of the coated propellant, this material will delay the burning rate of the coated propellant during combustion, so it is also possible to change the thickness of the coating layer to affect the burning time, and further control the numerical value of the longitudinal overload in the chamber of the guided projectile. Under the premise that the charge structure is 27/37H+23/19HB₁₁ (MC:B=7:3), the total charge mass is 18.20kg, and other parameters remain unchanged, only by changing the mass ratio of the coating layer of the coating propellant, which are 9%, 11%, 13% and 15%, respectively, numerical simulation of internal ballistic overload of guided projectiles is carried out. The corresponding projectile muzzle velocity, maximum overload and overload curves are calculated as shown in Table 4, Figure 6 and Figure 7.

Table 4. Influence of coating layer thickness on the internal ballistic overload value

Coating layer mass percentage /%	At the point of maximum overload /ms	Maximum overload /g	Projectile muzzle velocity / $m \cdot s^{-1}$
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9	8.52	18242.75	1098.72
11	8.57	17729.72	1091.33
13	8.59	17508.95	1087.04
15	8.62	17209.00	1081.26

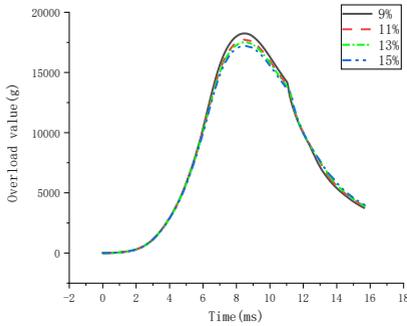


Fig. 6. *a-t* curves of different mass ratios of the coating layer.

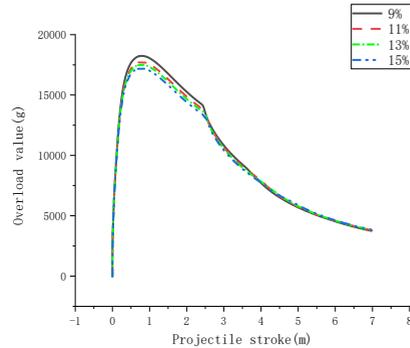


Fig. 7. *a-l* curves of different mass ratios of the coating layer.

It can be seen from Table 4, Figure 6 and Figure 7 that when the combustion time point of the propellant charge is around 8.55ms, the launch overload generated by the combustion in the chamber of the coated mixed charge with different coating layer mass percentages selected by the simulation calculation reaches the highest peak value. With the increase of the coating layer thickness of the coated propellant, the smaller the maximum launch overload value of the inner ballistic of the guided projectile, and the lower the projectile muzzle velocity; it can also be seen that the effect of the coating layer thickness on the launch overload is greater than that on the muzzle velocity. When the mass percentage of the coating layer increases from 9% to 15%, the launch overload value in the projectile chamber decreases by 5.67%, and the muzzle velocity of the projectile decreases by 1.59%. Therefore, it can be considered to increase the mass percentage of the coating layer of the coated propellant to reduce the value of the launch overload in the chamber of the guided projectile, but the thickness of the coating layer needs to be appropriately increased to avoid unreasonable structure of the propellant charge.

4 Conclusion

According to the charge design characteristics of a large-caliber suppressing artillery and the combustion characteristics of the coated propellant, one-dimensional two-phase flow calculation model for the inner ballistic is established. The numerical variation law of the inner ballistic overload of the guided projectile is obtained by simulation, and the feasibility of the model is verified. Comparing the simulation results of different filling methods under the coated mixed charge structure, the analysis shows that:

- The increase of the charge mass makes the projectile gain more kinetic energy, which increases the muzzle velocity of the projectile to a certain extent, but the overload impact of the inner ballistic of the guided projectile will also increase, so the charge mass cannot be blindly increased in the process of charge design.
- As a kind of flame retardant and insensitive material, TOX is added to the outer layer of the coated propellant, which promotes the combustion of the coated propellant to be

delayed. With the increase of the thickness of the coating layer and the proportion of the coated propellant in the mixed charge ratios, the longitudinal overload and the muzzle velocity in the bore of the guided projectile will be decreased to a certain extent, and the time point when the maximum overload occurs will be delayed, which provides a basis for the development of a new type of high muzzle velocity and low overload propellant charge design.

- Under the structure of the coated mixed charge, the influence of the proportion of coated propellant in different mixed charge ratios and the coating layer thickness of coated propellant on the launch overload of the guided projectile is greater than the muzzle velocity of the projectile, and the effect of reducing the firing overload in the chamber by increasing the proportion of coated propellant in different mixed charge ratios is the most significant.

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