Simulation of Double One-dimensional Two-phase Flow of Single Coated Propellant Internal Ballistic

Jihong Yin¹,a, Ping Du¹*, Fengqiang Nan¹ and Dongyao Liu²

¹ School of Chemical Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu, 210000, China
² School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu, 210000, China

*a injianhong@njust.edu.cn
*Corresponding author’s e-mail: dp1314@163.com

Abstract. In this paper, based on the one-dimensional two-phase flow model, we established a model of a single coated propellant and wrote the corresponding software. Using software to simulate the internal ballistic process of a 105mm tank gun, the calculation results are compared with the experimental results of the actual coated propellant. The results show that the calculated values are in good agreement with the experimental values.

1. Introduction
In modern warfare, with the application of modern technology in combat, the combat effectiveness of artillery is getting higher and higher. In the propellant, changing the formula and the development process of the missile weapon, increasing the range and power of the artillery require a lot of test data. The use of computer programming to simulate the internal ballistic process of the artillery can effectively reduce the test cost. The internal ballistic theory of two-phase flow is mainly based on the two-phase hydrodynamics, which can describe the ignition process in the artillery charge and the changing process of various parameters in the combustion field. At present, the domestic one-dimensional two-phase flow theory is mainly used to study and analyze the internal trajectory process of large-caliber balance guns and medium-caliber counterbore bullets. According to the characteristics of its charge, we build models and conduct computer simulations to analyze the characteristics of the flow field distribution, pressure waves and safety[1-5]. Zhang Xiaobing[6] simulated and analyzed the physical process of the full trajectory with a caliber artillery equipped with a shelling piercing projectile. Fu Lihua[7] and others used the two-step component CTVD calculation format to calculate the one-dimensional two-phase flow model, and obtained the parameter distribution at different times in the bore of the recoilless gun. During his master's degree, Yang Chao[8] carried out the internal ballistic process modeling and numerical calculation of the composite charge structure of large-caliber guns. It is mainly a mixed charge of granular propellant, rod propellant and tubular propellant. The main models of these studies are established on the basis of conventional charges, and there is little research on the charge technology of coated propellants. In this paper, We established a one-dimensional two-phase flow model of a single coated propellant and calculated it using the MacCormack method, to compile a calculation program for simulation, and combined with the experimental data of 105mm armor-piercing projectile for analysis and comparison.
2. Establishment of mathematical model

Two-phase fluid dynamics is one of the important theories to study the process in the artillery chamber. Therefore, the accuracy of the two-phase flow model determines the accuracy of the simulation results.

2.1. Basic assumptions
(1) The solid phase composed of gunpowder particles is continuously distributed in the gas phase, that is, the gunpowder particles are treated as a quasi-fluid with continuous medium characteristics;
(2) 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 coordinates \( x \) and time \( t \);
(3) Individual gunpowder particles obey the laws of geometric combustion and exponential combustion;
(4) The shape, size and performance of gunpowder particles should be kept strictly and the thickness of the coating layer should be uniform;
(5) The instant when the cladding layer finishes burning and the substrate starts burning is continuous;
(6) The inner hole and outer surface of the coated propellant are covered.

2.2. Mathematical model

2.2.1. One-dimensional two-phase flow conservation equations in the main charge area

(1) Gas mass conservation equation

\[
\frac{\partial}{\partial t} (\phi_c \rho_g A) + \frac{\partial}{\partial x} (\phi_c \rho_g u_g A) = \dot{m}_b A + \sum_k \dot{m}_{ign,k} A + \dot{m}_g A
\]

In the formula, \( \phi_c \) is the gas phase porosity; \( \rho_g \) is the gas phase density; \( u_g \) is the gas phase velocity; \( \dot{m}_b \) is the gas velocity of the coated gunpowder; \( \dot{m}_g \) is the flow rate of the igniter gas injected into the main charge bed by the ignition hole of the ignition tube and \( \dot{m}_{ign,k} \) is the \( k \)th kind of igniter original igniter gas flow; \( A \) is the cross-sectional area of the bore.

(2) Solid-phase mass conservation equation

\[
\frac{\partial}{\partial t} (\phi_s \rho_b A) + \frac{\partial}{\partial x} (\phi_s \rho_b u_b A) = -\dot{m}_b A
\]

In the formula, \( \rho_b \) is the material density of gunpowder; \( \phi_s \) is the volume ratio of gunpowder; \( u_b \) is the moving speed of granular medicine.

(3) Gas phase momentum conservation equation

\[
\frac{\partial}{\partial t} (\phi_c \rho_g u_g A) + \frac{\partial}{\partial x} (\phi_c \rho_g u_g^2 A) + \rho_o \frac{\partial p}{\partial x} = -f_s A + \dot{m}_b u_b A + \sum_k \dot{m}_{ign,k} u_{ign,k} A + \dot{m}_g u_{ign,g} A
\]

In the formula, \( f_s \) is the interphase resistance; \( u_{ign,g} \) is the axial jet velocity component of the ignition gas injected into the main charge bed by the ignition hole of the ignition tube; \( u_{ign,k} \) is the axial component of the injection velocity of the ignition gas of the \( k \)th ignition element in the bore.

(4) Solid phase momentum conservation equation

\[
\frac{\partial}{\partial t} [(\phi_s \rho_b u_b A) + \phi_s \rho_b u_b^2 A] + \phi_s A \frac{\partial p}{\partial x} + A \frac{\partial (\phi_s R)}{\partial x} = f_s A - \dot{m}_b u_b A
\]

In the formula, \( R \) is the stress between the powder particles.

(5) Gas phase energy conservation equation
\[
\frac{\partial}{\partial t}[\phi \rho_g A(e_g + \frac{u^2}{2})] + \frac{\partial}{\partial x}[\phi \rho_g u A(e_g + \frac{p}{\rho_b} + \frac{u^2}{2})] + p \frac{\partial \phi A}{\partial t} = m_b A \left( e_b + \frac{p}{\rho_b} + \frac{u^2}{2} \right) + \dot{m}_g H_{ign,g} A + \sum_k m_{ign,k} H_{ign,k} - f u_b A - \frac{q_b}{A} A
\]

In the formula, \( e_b \) is the potential of gunpowder; \( H_{ign,g} \) is the stagnation enthalpy of ignition gas in the ignition tube; \( H_{ign,k} \) is the stagnation enthalpy of ignition gas from the k-th ignition element; \( q_b \) is the heat exchange between the i-th granular medicine and the gas phase.

### 2.2.2. Auxiliary equation

1. **Equation of state**

   \[
   p \left( 1 - \frac{\alpha}{\rho_g} \right) = RT_g
   \]

   In the formula, \( \alpha \) is the gas capacity of gunpowder.

2. **Burning rate of gunpowder**

   \[
   \frac{de_b}{dt} = u_b p^n
   \]

   Cladding:

   \[
   \frac{de_1}{dt} = u_1 p^n
   \]

   Matrix propellant:

3. **Gas generation function:**

   \[
   \psi = \begin{cases}
   \chi_e Z_b \left( 1 + \lambda_b Z_b + \mu_b Z_b^2 \right) & (0 < Z \leq \frac{e_b}{e_1 + e_b}) \\
   \chi_i Z_i \left( 1 + \lambda_i Z_i + \mu_i Z_i^2 \right) & (\frac{e_b}{e_1 + e_b} < Z \leq 1) \\
   \chi_s \xi \left( 1 + \lambda_s \xi \right) & (Z > 1)
   \end{cases}
   \]

   In the formula, \( e_b \) is the thickness of the coating layer; \( e_1 \) is the 1/2 are thickness of the base propellant and \( \lambda_b, \mu_b, \chi_b, \lambda_i, \mu_i, \chi_i, \lambda_s, \mu_s \) is the shape function, which can be obtained.

4. **Interphase resistance:**

   \[
   f_{s,i} = C_{\beta} \frac{1-\phi_i}{\phi_i} \left| u_g - u_{pi} \right| (u_g - u_{pi}) \rho_g / dp_i
   \]

   \[
   C_{\beta} = \begin{cases}
   C_{\beta_i} & \phi \leq \phi_0 \\
   C_{\beta_i} \left( \frac{1-\phi_i}{\phi_i} / \frac{1-\phi_0}{\phi_0} \right)^{0.21} & \phi_0 < \phi < 0.977 \\
   0.45 & 0.977 \leq p \leq 1
   \end{cases}
   \]

   \[
   C_{\beta_i} = \begin{cases}
   0.31(e_g R_{\phi})^2 - 2.5 R_{\phi} (R_{\phi}) + 6.33 & R_{\phi} < 20000 \\
   1.10 & R_{\phi} \geq 20000
   \end{cases}
   \]
In the formula, $d_{p_i}$ is the equivalent diameter of the two granular propellants; $C_D$ is the drag coefficient.

(5) Stress between particles:

$$R_i(\phi) = \frac{Ep_i}{1-\phi} \cdot \frac{\phi}{\phi_0} (\phi - \phi_0) \exp[(K_0 + K_1(\phi - \phi_0))]$$

(13)

In the formula, $\phi$ is the porosity of the granular drug interval and $\phi_0$ is the natural accumulation porosity.

(6) Surface temperature of gunpowder:

$$T_{ps} = T_{ps0} + (T_g - T_{ps0})[1 - e^{-\frac{\frac{h}{K_p}a_{t_f}}{K_p}} (1 - \frac{h}{K_p} \sqrt{a_{t_f}})]$$

(14)

In the formula, $T_{ps}, T_{ps0}, T_g$ are the surface temperature of the gunpowder particles, the initial solid temperature and the gas temperature; $a_{t_f}$ is the thermal conductivity of the gunpowder; $K_p$ is the thermal conductivity.

In the auxiliary equation (6), (10), (11), (12), (13), (14) mainly see the literature [9].

3. Calculation results and analysis

We selected a 105 mm high-pressure gun as a simulation example for comparison. On the artillery, we selected 21/19HB11 coated propellant for testing. We measured the p-t curve using a piezoelectric pressure measurement system and the projectile velocity measured by the coil target. We use the same loading conditions as the shooting test for numerical simulation calculations, and the internal ballistic performance curves are shown in Figures 1 to 3.

3.1. Comparative analysis of numerical calculation and test results

Table 1. Measured data and simulated calculation results of artillery

| $p_m$ / MPa | $v_0$ / m·s⁻¹ |
|-------------|---------------|
| Measurements | 562.02        | 1705.3        |
| Calculated  | 562           | 1730.01       |
| error       | 0.004%        | 1.45%         |

Figure 1. Comparison curves of measured and numerical simulation results of gun chamber pressure
Comparing the calculation results of the one-dimensional two-phase flow model of the high-pressure gun with the measured data of the gun, the results are shown in Figure 1 and Table 1. It can be seen from Table 1 that among the special point values, the calculated values are compared with the experimental data and found to be a good match, indicating that the program is available. Figure 1 is the pressure curve of each point in the bore. Figure 2 is the pressure wave curve. It can be seen from the figure that the first peak is a positive value. Due to the continuous generation of high-pressure gas in the bottom fire, the pressure at the beginning of the borehole is always higher than the bottom pressure of the projectile. The first negative pressure value is because the flame wave reaches the bottom of the projectile, and the particle density at the bottom of the projectile is high, causing the bottom pressure of the projectile to be greater than the bottom pressure. Figure 3 is the curve of projectile velocity with time.

4. Conclusion

Comparing the simulation results with the experimental data, we find that the maximum pressure in Table 1 fits well with the muzzle velocity, the errors are all less than 2%. The curve simulation in Figure 2 has a certain error, because the model has a certain difference with the actual combustion, which may be due to the error caused by the model being established under certain assumptions.

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