Corrected Internal Ballistic Simulation of High Chamber Pressure Gun

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Abstract. In view of the high initial velocity and chamber pressure of the high chamber pressure gun, the equation of state of gunpowder gas which is closer to the actual situation is adopted. Then considering the influence of the air resistance at the front of the projectile, the change of the combustion speed parameter in different pressure sections, both the specific heat ratio of the gunpowder gas and the constant volume specific heat change with the pressure and temperature, and the effect of erosive burning, the traditional classical internal ballistic model is modified. And the corresponding physical and mathematical models are established, the analogous calculation programs are compiled, the theoretical calculations and experimental results are compared. The results show that compared with the traditional classical internal ballistic model simulation, the simulation results of the modified ballistic performance of the high chamber pressure gun are more consistent with the experimental results.

1. Introduction
Simulating the calculation of the internal ballistic performance of the propellant charge is a major method. Its application can greatly shorten the research cycle of the propellant charge, save research costs and improve safety. In recent years, there have been numerous studies on the establishment and application of internal ballistic models[1-3]. At present, the simulation of the internal ballistic performance of the launching charge is based mainly on the traditional classical internal ballistic calculation method[4]. Based on the Nobel-Abel equation, the method uses the same exponential burning rate formula over the entire pressure range, regardless of the specific heat ratio of the gunpowder gas and the constant volume specific heat change with pressure and temperature, ignoring the influence of the air resistance at the front of the projectile and the effects of erosive burning. In the case of the low loading density, low chamber pressure and low initial velocity, the results of numerical simulation of internal ballistics are in good agreement with the actual situation.

However, in high chamber pressure guns, due to the use of high-energy propellants and high charge density, the chamber pressure and initial velocity have been greatly improved, and the combustion environment (pressure interval) of the propellant has also changed[5]. Based on the classical internal ballistic calculation method, this paper adopts the state equation of gunpowder gas which is more in line with the actual situation of high chamber pressure gun firing process, considering the air resistance in the front of the projectile and erosive burning, the change of combustion velocity parameters in different pressure sections and specific heat ratio and constant volume specific heat change with time and temperature. The traditional internal ballistic model has been modified by those factors. Corresponding physical and mathematical models are established. Calculation procedures are compiled, and the theoretical calculations and experimental results are compared. The model is made
in the hope that the study will promote the internal ballistic performance prediction and charge design of the high chamber pressure gun.

2. Corrected internal ballistic model of high chamber pressure gun

2.1 Gunpowder gas equation

At present, the equation of state of gunpowder gas commonly used in internal ballistic simulation is the Nobel-Abel equation:

\[ p(v - \alpha) = RT \]  

In the formula: \( v \) indicates the specific volume of the gas; \( \alpha \) represents correction amount related to the molecular volume per unit mass of gas, referred to as covolume in internal ballistics; \( R \) is the gas constant associated with the gas component.

However, in high chamber pressure gun, due to the enormous increase in chamber pressure, the charge amount increases, the density of gunpowder gas becomes larger, and the interaction between gas molecules is enhanced. If the Nobel-Abel equation is continuously used, it will produce a larger error. Therefore, in the calculation of the internal ballistics of the high chamber pressure gun, Van der Waals gas state equation is used to improve the calculation accuracy.

\[ (p + \frac{a}{v^2})(v - \alpha) = RT \]

In the formula: \( a \) is the coefficient of intermolecular interaction.

2.2 Gunpowder burning rate equation

Burning rate equation of internal ballistics is generally in the form of exponential:

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

In the formula: \( u_1 \) and \( n \) are constants related to gunpowder properties and gunpowder temperature, respectively called the burning rate coefficient and the pressure index.

Currently, the burning rate equation is usually obtained from closed bomb experiment. In the classic internal ballistic calculation, the average burning rate coefficient and pressure index parameters under a certain pressure range are usually selected[6]. However, in high chamber pressure gun, the ambient pressure range of gunpowder combustion becomes larger, and the single average burning rate coefficient and pressure index parameters can no longer reflect the actual combustion of the propellant. Therefore, based on the experimental results of closed bomb, the burning rate coefficient and the pressure index parameter are processed in stages, and different burning rate coefficients and pressure indexes are selected under different pressure sections.

In addition, when the gunpowder is burned in the bore, the phenomenon of erosive burning is caused by the difference between the movement of the gunpowder gas stream and the moving speed of the gunpowder pellet. Generally, when the gas flow rate is lower than 100 m/s, the erosive burning performed is small, and in the burning rate equation, the influence is ignored. However, in high speed artillery, the airflow speed before the end of the burning of gunpowder can reach more than 1000m/s, and the erosion becomes very obvious[7]. Therefore, in high chamber pressure guns, the establishment of the burning rate equation must consider the effects of erosive burning. Therefore, based on the original exponential function, a correction term for the airflow velocity is added.

\[ \frac{de}{dt} = u_1 p^n + k_v v \]

In the formula: \( k_v \) is erosive burning coefficient; \( v \) is projectile velocity.

In principle, \( v \) in formula (4) should be the velocity of the gunpowder gas flow relative to the gunpowder pellet, but for convenience, it can be taken as the projectile velocity, and the difference can be corrected in the value of \( k_v \), so \( k_v \) is erosive burning coefficient which is corresponding to the
velocity of the projectile.

2.3 The specific heat ratio of the gunpowder gas and the constant volume specific heat
In the past internal ballistic theory, due to the small range of pressure and temperature spanning the
gunpowder gas during the design process, for the convenience of calculation, the gunpowder is
regarded as a rigid ball of Clausius gas, that is, the covolume is regarded as a constant, there is no
interaction between the molecules; the same is true for the constant volume specific heat $C_v$ and the
specific heat ratio of the gunpowder gas $k$ as a constant. In fact, the constant volume specific heat $C_v$
and the specific heat ratio $k$ change with temperature and pressure. Especially in high chamber
pressure guns, the range of temperature and pressure changes is larger. Therefore, the previous
approximation can no longer meet the requirements and needs to be used as variables.

Considering the relationship between the internal pressure and the interaction potential of gas
molecules in the Van der Waals equation and the interaction potential of the mixed gas, the calculation
method is as follows:

$$C_v = C_{v_0} + \frac{\partial}{\partial T}(E - E_0) = C_{v_0} + \frac{RA}{16(v - \alpha)}(3 - \frac{\alpha}{v - \alpha})$$

$$k = \frac{C_p}{C_v} = 1 + \frac{TR^2[1 - \frac{\alpha}{4(v - \alpha)}]}{C_v(v - \alpha)[\frac{RT}{v - \alpha} + (1 - \frac{\alpha}{v})\frac{\partial \phi}{\partial v} - \frac{\phi}{v}]}$$

2.4 Air resistance at the front of the projectile
During the movement of the projectile, a shock wave is formed owing to the continuous compression
of the air before the projectile. The presence of the shock wave increases the pressure of the gas after
the shock wave and hinders the movement of the projectile. That is the shock wave resistance of
the air at the front of the projectile. Therefore, for high chamber pressure guns with high initial velocity, it
is necessary to add the pressure in the front of the projectile in the motion equation.

$$(p - p_R)S = q dn \frac{dv}{dt}$$

Among them, $p_R = p_a[1 + \frac{k(k + 1)}{4} \left(\frac{v}{c_1}\right)^2 + k \frac{v}{c_1} \left(1 + \frac{k + 1}{4} \left(\frac{v}{c_1}\right)^2\right)]$

In the formula: $p_a$ is ignition pressure; $c_1$ is sound velocity of undisturbed air before shock wave; $k$ is
Adiabatic index in air.

2.5 Establishment of internal ballistic model
Based on the above corrections, an internal ballistic physics and mathematical model that is more in
line with the actual combustion conditions of high chamber pressure guns is established.

2.5.1 Basic assumption
- Gunpowder gas obeys the Van der Waals equation.
- Gunpowder follows the law of geometric combustion.
- Burning rate equation uses the exponential equation, and the high and low pressure sections
  use different combustion coefficients and pressure indices.
- Use factor $\phi$ to consider other secondary skills.
- The squeezing of the sling into the squall line is instantaneous, regardless of the squeezing
  process.
After the elastic band is squeezed into the twist line, the airtightness is good and there is no air leakage.

Use equation (4) to characterize the effect of erosive burning on the burning rate of the propellant.

Characterize the air resistance at the front of the projectile with equation (7).

Use equations (5) and (6) to characterize the effect of gunpowder gas temperature and pressure on the specific heat ratio of the gunpowder gas and the constant volume specific heat.

Based on the above assumptions, the following basic equations can be derived:

1. Shape function:
   \[
   \psi = \begin{cases} 
   \chi Z (1 + \lambda Z + \mu Z^2) & (Z \leq Z_k) \\
   \chi_s & (1 \leq Z \leq Z_k) \\
   1 & (Z \geq Z_k)
   \end{cases}
   \]
   (1)

2. Gas state equation:
   \[
   (p + \frac{a}{v^2})(v - \alpha) = RT
   \]
   (9)

3. Burning rate equation:
   \[
   \frac{dZ}{dt} = \begin{cases} 
   \frac{u_i p^n + k_v v}{e_i} & (Z \leq Z_k) \\
   0 & (Z \geq Z_k)
   \end{cases}
   \]
   (10)

4. Energy equation:
   \[
   C_i T_i \omega - C_j T_j \omega = \frac{1}{2} \phi m v^2
   \]
   (11)

5. Motion equation:
   \[
   (p - p_k)S = \phi m \frac{dv}{dt}
   \]
   (12)

According to the above, the internal ballistic mathematical model of the high chamber pressure gun was modified, and the internal ballistic simulation calculation program was designed by VB6.0 programming. The fourth-order Runge-Kutta method is used to solve the established basic equations of internal ballistics.

### 3. Simulation calculation and result discussion

Taking 100mm caliber high pressure gun as an example to calculate, the calculation parameters are as follows:

1. Artillery elements: the volume of the powder chamber \( V_0 = 8.71 \text{dm}^3 \); sectional area of barrel \( S = 0.7854 \text{dm}^3 \); projectile stroke \( l_g = 4.789 \text{m} \); projectile weight \( m = 6.35 \text{kg} \).

2. Charge elements: propellant web size \( 2e_1 = 2.7 \text{mm} \); bore diameter \( d_0 = 1 \text{mm} \); gunpowder length \( 2c = 30 \text{mm} \); charge amount \( \omega = 6.8 \text{kg} \); powder density \( \rho_1 = 1630 \text{kg/m}^3 \); force capacity \( f = 1230 \text{kJ/kg} \); covolume \( \alpha = 0.001 \text{m}^3/\text{kg} \).

The internal ballistic performance of the high chamber pressure gun was calculated by software simulation, and the output \( p-t \) curve was compared with the measured data curve to obtain Figure 1.

It can be seen from Figure 1 that the chamber pressure curve of the conventional internal ballistic simulation calculation program rises faster before reaching the maximum pressure, so that the maximum chamber pressure time is advanced, and after the maximum pressure is reached, the
chamber pressure is reduced faster. There is a great difference in the pressure curve. However, the pressure curve of the corrected internal ballistic simulation calculation program is slower before reaching the maximum pressure. The time to reach the maximum pressure point is very close to the measured curve. After reaching the maximum pressure point, the chamber pressure is also slowed down. It is better to match the measured curve.

4. Conclusions
(1) By using the state equation of the gunpowder which is closer to the actual situation, considering the influence of the air resistance at the front of the projectile and the change of the combustion speed parameter in different pressure sections, mean while, both the specific heat ratio of the gunpowder gas and the constant volume specific heat changes with the pressure and temperature, and the effect of erosive burning are also considered, the internal ballistic calculation model and software of high chamber pressure guns were established.

(2) The comparison between calculation and experimental results shows that compared with the traditional classical internal ballistic model simulation, the simulation results of the modified ballistic performance of the high chamber pressure gun are more consistent with the experimental results.

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