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Interior ballistic prediction of gun propellants based on experimental pressure-apparent burning rate model in closed vessel

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Abstract

A new experimental pressure-apparent burning rate model was established based on the recorded pressure-time data in the closed vessel to study the actual burning gas generate rate of a propellant whose form function is not available. The new burning model can replace the Vieille's law and form function of propellants in the interior ballistic equations to predict the interior ballistic performance of gun. As distinct from the traditional geometric form function based burning rate model, the new model introduced the concept of relative pressure impulse related to the actual burnt web thickness of propellant statistically. The apparent burning rate was expressed by the propellant mass fraction burnt vs. relative pressure impulse curve. Based on the recorded experimental pressure time data of three kinds of propellants, such as 12/1, 13/7 and 13/19 single-base propellants, numerical calculation was carried out using the computer program of the new model. And numerical calculation results were different form those of the traditional geometric form function based burning rate model. The new experimental pressure-apparent burning rate model is more suitable for the actual combustion circumstances of propellants in the closed vessel, for which is ultimate independent of the various grain sizes and have taken account of the influence of chamber pressure on the actual burning rate. The interior ballistic simulation of selected gun propellants was conducted using the new burning rate model. The results predicted by the new model show a good agreement with the classic interior ballistic predication results though the agreement with the experimental results is still to be improved.

Keywords : propellant, closed vessel, burning rate models, interior ballistic, simulation

1. Introduction

Classic interior ballistic method includes the form function and burning rate equations of gun propellants based on the geometrical burning rule, equations of projectile motion and energy conservation equation[1)-3)]. Except the chemical kinetics computing methods[4)], the burning rate of gun propellants is obtained by closed vessel test or gun firing, which is dependent on the pressure usually described by Vieille's law shown in Equation (1)[5)]

$$u(p) = \mu_1 p^n \tag{1}$$

Where μ_1 is the burning rate coefficient and n is the pressure exponent.

The main work carried out with a closed vessel consists in pressure measurements during the combustion of a propellant, i.e. the pressure history and the pressure maximum[6),7)]. These measurements at different loading densities allow calculating the thermodynamic properties of the combustion gas (covolume and propellant force constant), the dynamic vivacity as well as burning rate of propellants based on the Nobel-Abel equation of state.

The Nobel-Abel equation of state is used to determine the amount of propellant that must have burn (mass fraction) to produce the experimentally measured pressure. The measured pressure should be corrected considering the heat loss to the wall of closed vessel. A form function related to the current dimensions of the remaining propellant is used to calculate the surface area of propellant for each pressure-time point. The burning rate is then calculated using the derivative of the mass generated at each time step according to the equation (2)[8), 9), 15)]

$$\frac{d\Psi}{dt} \propto A\ (p)\,u\ (p) \tag{2}$$

Where A is the surface area of remaining propellant, $d\Psi/dt$ is time derivative of propellant mass fraction burnt, i.e, burning gas generation rate.

It is well known that the derivation of propellant burning rate is based on the geometry of grains and parallel layer burning rule and expressed as Vieille's law. The Vieille burning rate is still used as a burning model of propellant in gun bore although it bears no relation to thermodynamic process occurred in gun bore.

Recently, theoretical models of two-phase flow in gun bore and their solutions have been developed[10)], which are able to study the space distribution of pressure and gas-flow velocity, but geometrical burning rule and from function are still used as one of the main assumptions in these models.

Obviously, geometrical burning rule is little more than ideal. According to the assumption of this rule, all grains should have same shape and dimensions and burn in parallel layers in the direction that is perpendicular to grains' surfaces after ignition of all surfaces. Actually, the uniformity of burning for all propellant grains are directly influenced by many factors such as the variation in shapes and dimensions from one grain to another grain, and the difference in the ignition condition as well as the circumstance that the burning charges. The actual burning rule should reflect a statistical property, and there exits a deviation with the burning rate determined by form function based on geometrical burning rule.

Especially, as for the deterred and multi-layer coated propellants, conventional burning rate calculation method can still employ the geometry form function method[11)]. For the deterred propellants, the deterred layer possesses a continuously increasing burn rate from outer layer to the inner core. The distribution function of deterrent inside the deterred layer can be determined by experiments. It can be assumed that the propellant force is constant for each layer[12)]. A multi-layer coated propellant generally consists of two or three distinct coating layers. Since the coating layers are very thin compared to the burning thickness of propellants, it can be assumed that the burning rate of coating layers is constant during combustion process. When the outer coating layer is consumed, the inner part of the propellants start to burn according to the geometry burning rules[13)]. However, for the multi-layer coated propellants which have complex shape of inner hole, if the diameter of inner hole is relatively large, or the coating layers are brittle, perhaps the coating layers will not finished burning simultaneously. Thus, some surface coating layers on the inner holes will be broken, and the inner holes begin to burn in advance. In that case, it will become very difficult to calculate the burning rate of coated propellants.

Moreover, if the form function of some kinds of propellant is not available, it is impossible to determine the burning rate by the traditional method. Eisenreich et al[14),15)] modified the Vieille's law to account for the temperature dependence of the burning rate or the combustion in porous propellants by a simplified analysis of the heat flow in the solid phase. The dependence of the burning rate on initial temperature, on phase transitions, porous structure and gaseous reactions can be described by the new burning rate model.

The theory of potential equilibrium for interior ballistics established by Bao et al[16)] can explain the actual burning rate of propellants in gun bore by means of the point of potential equilibrium. Actual burning rate equation of propellants in the new theory of potential equilibrium was derived from the firing data of gun directly. The closed vessel tests need not be used. The corresponding solving method of interior ballistics can be derived and constitute a new interior ballistics system which was different from the classical system on the basis of geometrical burning rule. However, it was still too complex to be applied in the ballistic prediction extensively. Obviously, simple ballistic method is rapid and efficient and can give useful results for charge estimation and prediction of performance of gun.

In the present work, the apparent burning rate of propellant was deduced from closed vessel test data based on the concept of relative pressure impulse related to the actual burnt web thickness of propellant statistically. Then it was incorporated into the equations of classic interior ballistic to replace the form function and equation of burning rate to establish a novel ballistic prediction method for gun propellants. The new method doesn't need the form function calculation. It is very suitable for the propellants whose form function is not available, such as the coated consolidated propellants. Simulation results for a selected gun propellant charge showed a good agreement with the classic interior ballistic predicted results.

2. Concept of relative pressure impulse

From the point view of form function, the most important variable is the actual burnt web thickness during combustion. For a special form of propellant, the surface area can be calculated from the actual burnt web thickness and form function. For a propellant whose form function is not available, we need to choose a measurable quality which is related directly to the actual burnt web thickness to replace the immeasurable nominal burnt web thickness.

Many researches[17),18)] showed that the burning layer concept can still be used to the calculation of propellant burning rate when the form function is not available. The thickness of the burning layer distributes in a certain range (the pressure-time ($p-t$) curve of propellant recorded in closed bomb test should reflect thick or thin of propellant's burning web thickness. Thinner propellants finish burning faster, while thicker propellants take more time to finish burning). Therefore, the normalized pressure impulse is defined as

$$Z_p = \frac{\int_0^t p dt}{\int_0^{tk} p dt} = \frac{I}{I_k} \tag{3}$$

as an independent variable, then $\Psi - t$ curve can be converted into $\Psi - Z_p$ curve which may be expressed as the following cubic polynomial equation

$$\Psi = \Psi_0 + \Psi_1 Z_p + \Psi_2 Z_p^2 + \Psi_3 Z_p^3 \tag{4}$$

and it describes the actual burning gas formation rule in closed vessel. Equation 4 is the experimental pressure-apparent burning rate model related to the burnt layer thickness statistically.

The coefficient Ψ_0, Ψ_1, Ψ_2, Ψ_3, Ψ_4 in Equation 4 can be solved by least-squares fitting method based on the experimental data points. The formula of solving is showed as follows

$$\begin{cases} \Psi_0 \times 4 + \Psi_1 \sum Z_\pi + \Psi_2 \sum Z_\pi^2 + \Psi_3 \sum Z_\pi^3 = \sum \Psi_i \\ \Psi_0 \times \sum Z_\pi + \Psi_1 \sum Z_\pi^2 + \Psi_2 \sum Z_\pi^3 + \Psi_3 \sum Z_\pi^4 = \sum Z_\pi \Psi_i \\ \Psi_0 \times \sum Z_\pi^2 + \Psi_1 \sum Z_\pi^3 + \Psi_2 \sum Z_\pi^4 + \Psi_3 \sum Z_\pi^5 = \sum Z_\pi^2 \Psi_i \\ \Psi_0 \times \sum Z_\pi^3 + \Psi_1 \sum Z_\pi^4 + \Psi_2 \sum Z_\pi^5 + \Psi_3 \sum Z_\pi^6 = \sum Z_\pi^3 \Psi_i \end{cases} \tag{5}$$

where i is the different data point number in the curve of $\Psi - Z_p$.

According to the classic interior ballistics, if the burning rate of propellant is proportional to the pressure, it can be expressed simplify by

$$u\,(p) = \mu_1 p \tag{6}$$

Actually, when the pressure in the combustion chamber is above the pressure of 100 MPa, the above Equation 6 is totally approximate to the actual combustion. Then the above equation can be wrote as

$$\frac{de}{dt} = \mu_1 p \tag{7}$$

Where e is the burnt web thickness. Integrating Equation 7

$$\frac{e}{\mu_1} = \int_0^t p dt = I \tag{8}$$

Where I is the pressure impulse at the pressure-time point. It is the area under the pressure-time curve along the time axis from the zero point to the instant pressure-time point. When the propellant is finished burning at burnt instant t_k

$$\frac{e_1}{\mu_1} = \int_0^{t_k} p dt = I_k \tag{9}$$

Where e_1 is the initial web thickness. I_k is the pressure impulse at the burnt point t_k. It is a constant for a specific propellant with certain web thickness.

From the Equation 8 and 9, the relative pressure impulse Z_p is a measurable quantity and proportional to the burnt web thickness when the burning rate of propellant is proportional to the pressure. Actually, even if the burning rate of propellants is described by the exponent equation, the relative pressure impulse is still statistically corresponded to the actual burnt web thickness under the same test conditions. Therefore, the point of maximum pressure of propellant in the closed vessel

$$Z_p = 1, I = I_k$$

will act as the boundary condition of Equation 4 to show a statistically property during closed vessel combustion.

The concept of relative pressure impulse based on the pressure-time data in the closed vessel can avoid the errors resulted from the variation of shape and dimensions of propellants. The new experimental pressure-apparent burning rate model is directly derived based on the concept of relative pressure impulse and recorded pressure time data in closed vessel, which is very different from the traditional method of form function. The new burning rate is not dependent on the form function calculation of propellants. Meanwhile, the influences of the pressure on burning rate during combustion process is considered, which can result in the synergetic effect of pressure and burning circumstance to increase the gas generation rate in closed vessel. Therefore, it is more practical to calculate the apparent burning rate, especially suitable for the propellants whose form function is not or difficult to available.

3. Interior ballistic equations based on the experimental pressure-apparent burning rate model

There are many interior ballistic models historically[3), 10)]. Three levels of interior ballistic models employed are the IBHVG2 lumped-parameter interior ballistic code; the XKTC one dimensional (1−D), two-phase flow interior ballistic code; and NGEN3 multidimensional, two-phase flow interior ballistic code.

In China, the classic interior ballistic model similar to the IBHVG2 is extensively employed in prediction of the gun performance. It can do a better job of gun performance than the two-dimensional, two-phase flow models. It contains equations representing the physics of the gun interior ballistic process. In general, the equations of the conservation of mass, momentum, and energy can be used to describe the physical process.

These equations are presented as follows.

Equation of form function

$$\Psi = \begin{cases} \chi Z\,(1 + \lambda Z + \mu Z^2), & 0 \le Z \le 1 \\ \chi_s Z\,(1 + \lambda_s Z), & 1 < Z \le Z_k \end{cases} \tag{10}$$

where Z is the relative burnt thickness. Z_k is the relative burnt thickness for multi-peroration propellant at all burnt point. χ, λ, μ are the characteristic coefficients related only to the geometrical shape and dimensions of grain. χ_s, λ_s are the characteristic coefficients of multi-perforation propellants in splintery burning stage.

Burning rate equation

$$\frac{\mathrm{d}Z}{\mathrm{d}t} = \frac{\mu_1}{e_1} p^n \tag{11}$$

Equations of projectile motion

$$\varphi m \frac{\mathrm{d}v}{\mathrm{d}t} = Sp \tag{12}$$

$$\frac{dl}{dt} = v \tag{13}$$

where m is projectile weight, v is the velocity of projectile, S is the bore area, φ is the coefficient of secondary works in terms of mean pressure in the bore. l is the projectile travel.

Energy equation

$$Sp\ (l + l_{\Psi}) = f\omega\Psi - \frac{\theta}{2}\varphi m v^2 \tag{14}$$

where

$$\theta = k - 1 \tag{15}$$

$$l_{\Psi} = l_0 \left[1 - \frac{\Delta}{\rho_p}(1 - \Psi) - \alpha\Delta\Psi \right] \tag{16}$$

$$\varphi = \varphi_1 + \frac{1}{3}\frac{\omega}{m} \tag{17}$$

$$\Delta = \frac{\omega}{V_0} \tag{18}$$

$$l_0 = \frac{V_0}{S} \tag{19}$$

Where, the variable k is the specific heat, V_0 is the bore volume, ω is the propellant charge weight (kg), Δ is the loading density of charge in the bore, l_0 is the traverse of projectile in the bore, ρ_p is the propellant density, α is the covolume, φ_1 is the resistance coefficient.

The mass burning rate of propellant in classic interior ballistic is mainly based on the assumption that the rate of burning is the same on all surfaces of grain, which results in the acceptance of geometric form function. However, as has been previously discussed, it is not true in the actual combustion process. Furthermore, we will show a deviation example in the section 3 for three kinds of propellants which has almost the same neutral burning behaviours. The equations of from function and burning rate of propellant in the classic interior ballistic are replaced by the experimental pressure-apparent burning rate model described in this paper. The new equations for interior prediction method are as follows.

Experimental pressure-apparent burning rate model

$$\Psi = \Psi_0 + \Psi_1 Z_p + \Psi_2 Z_p^2 + \Psi_3 Z_p^3 \tag{4}$$

Relative pressure impulse equation

$$Z_p = \frac{\int_0^t Pdt}{\int_0^{t_k} Pdt} \tag{20}$$

Equation of projectile motion

$$\varphi m \frac{\mathrm{d}v}{\mathrm{d}t} = Sp \tag{12}$$

Equation of projectile velocity

$$\frac{dl}{dt} = v \tag{13}$$

Energy equation

$$Sp\ (l + l_{\Psi}) = f\omega\Psi - \frac{\theta}{2}\varphi m v^2 \tag{14}$$

4. Comparison with traditional burning rate model

4.1 Experimental propellants

Table 1 lists the size of three kinds of single-base propellant grains in closed vessel test[19]. For the convinence of study, the three kinds of single-base propellant are designed with special size of roughly constant burning surface, i.e. nearly neutral burning. In table 1, D is outside diameter, d is inside diameter, $2e_1$ is web size of propellant, ρ_p is propellant density, and $2c$ is propellant length. The experimental loading density in closed bombs is 0.2 g·cm^{-3}. The igniter is 2# Nitrocellulose (NC) of 1.0 g.

4.2 Deviation of propellant mass fraction burnt

In order to compare the effect of shape of propellant on the mass fraction burnt, the deviation in the whole combustion procedure calculated using the model in this paper and using traditional form function method is showed in Figure 1. Figure 1 (a), (b) and (c) are $\Psi - Z_p$ curves of 12/1, 13/7 and 13/19 single based propellants, respectively. The curve 1 in the figure is $\Psi - Z$ curves calculated by the traditional form function method. The curve 2 in the figure is $\Psi - Z_p$ curve calculated by experimental pressure-apparent burning rate model.

As seen in Figure 1, the three kinds of single-base propellant showed a roughly constant burning surface. However, there is a significant deviation of burning gas generation rate between the traditional method and the new method in this study. For example, for 12/1 tubular single-base propellant, when it burned, the regressive burning properties of burning surface was minimum, and the $\Psi - Z$ curve calculated by the traditional form function method was similar to a diagonal line. With the increasing of the relative burnt thickness, the gas generation gradually increased to the maximum. However, the

Table 1 Size of three kinds of single based propellants grain.

Propellant	D[mm]	d[mm]	$2e_1$[mm]	2c[mm]	ρ_p[g · cm^{-3}]
12/1 single-base tubular grain	3.09	0.58	1.25	3.99	1.596
13/7 single-base cylindrical grain	7.61	0.63	1.43	9.59	1.583
13/19 rosette single-base cylindrical propellant	10.05	0.48	1.27	11.51	1.593

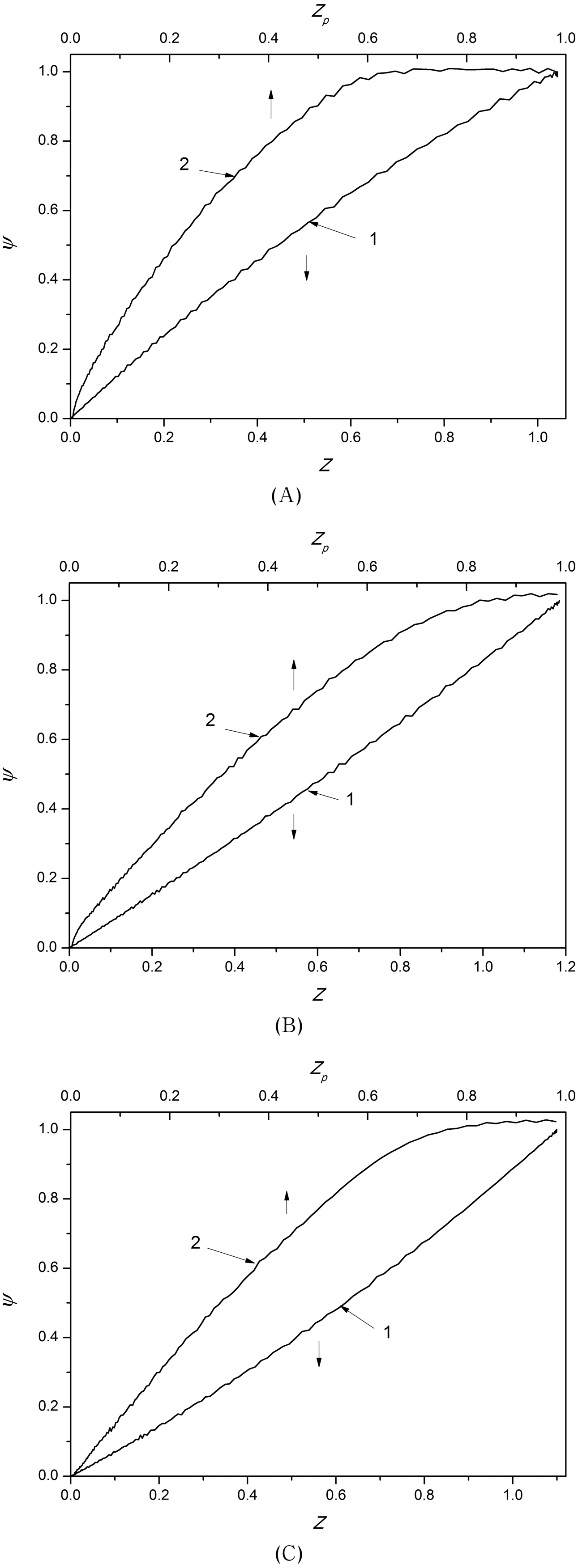

Figure 1 Comparison of $\Psi-Z_p$ curve of three kinds of propellants.
(A) 12/1 single-base propellant (B) 13/7 single-base propellant (C) 13/9 single-base propellant calculated by two kinds of different models : 1-Traditional form function method ; 2-experimental pressure-apparent burning rate model.

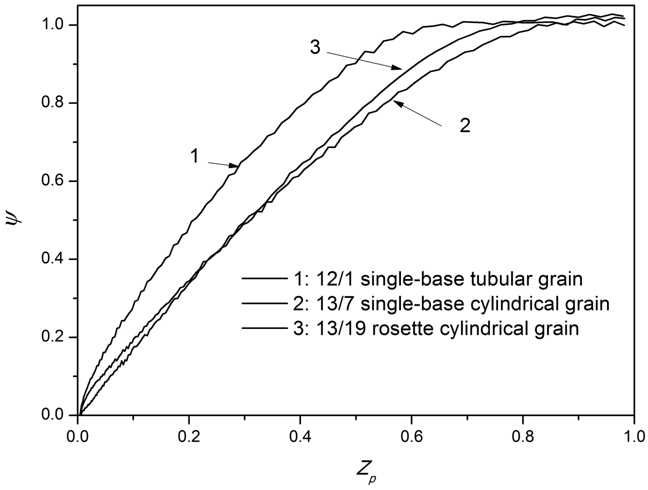

Figure 2 $\Psi-Z_p$ curve calculated by experimental pressure-apparent burning rate model.
(1) : 12/1 single-base tubular grain ; (2) : 13/7 single-base cylindrical grain ; (3) 13/19 rosette single-base cylindrical propellant

propellant mass fraction burnt calculated by the new burning model indicates the rapid increase in the initial burning stage, then gradually to the maximum earlier than that calculated by the traditional form function method.

Figure 2 shows the $\Psi-Z_p$ curve of three kinds of single base propellants using the experimental pressure-apparent burning rate model.

As seen in Figure 2, it indicates that at the beginning of propellant combustion, as the increase of relative pressure impulse, the gas generation increases, and then there is a platform of gas generation with no more increasing later. At the later combustion phase, the gas generation rate becomes slow. These numerical results are consistent with the actual burning circumstance of propellant in the close bomb. Obviously, influence of the pressure on the burning rate of 12/1 single-base tubular propellants is much bigger than the other two kinds of multi-perforation cylindrical propellants.

5. Interior ballistic simulation based on the experimental pressure-apparent burning rate model

Base on the above comparative research results, the new experimental pressure-apparent burning rate model will be used to predict the interior ballistic performance during the actual gun firing. In order to validate the new interior ballistic model incorporated with new experimental pressure-apparent burning rate model, a gun interior ballistic simulation compared with the classic interior model based on the same gun and actual charge data was conducted.

Given the following data of 100 mm gun, Bore area : 81.8 cm^3 ; Case volume : 7741 cm^3 ; Projectile travel : 474.30 cm ; Projectile weight : 15.6 kg ; Propellant charge weight : 5.6 kg.

The propellant charge is composed of double-base tubular propellant grains. Its size is listed in Table 2.

Table 2 Size of grain in 100 mm gun propellant charge.

Propellant	D[mm]	d[mm]	$2e_1$[mm]	2c[mm]	ρ_p[g.cm^{-3}]
18/1 double-base tubular grain	4.95	1.75	1.60	40.75	1.6

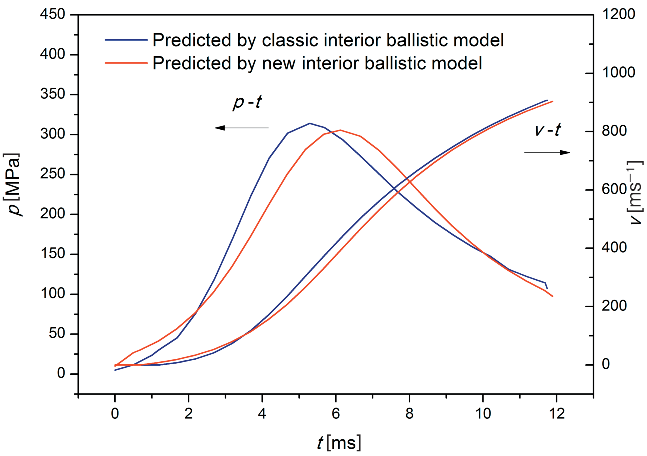

Figure 3 Mean pressure and projectile velocity vs. time curves as predicted by classic interior ballistic and new interior ballistic method based on experimental-apparent burning rate model.

The pressure and projectile velocity vs. time curve as predicted by the new interior ballistic method and classic interior ballistic method respectively is given in Figure 3.

The fitted mass fraction burnt function of double-base tubular grain is as follows.

$$\Psi = 0.0156 + 0.9945Z_p + 1.0154Z_p^2 - 1.0076Z_p^3 \quad (21)$$

The experimental peak pressure is 325.0 MPa, and the recorded muzzle velocity 900.0 ms^{-1}. The classic interior ballistic prediction of peak pressure is 314.0 MPa, and the predicted muzzle velocity 907.7 ms^{-1}. However, the new interior ballistic prediction based on the experimental pressure-apparent burning rate model in closed vessel of peak pressure is 305.8 MPa, and the predicted muzzle velocity 903.9 ms^{-1}. Obviously, the two kinds of interior ballistic methods indicate almost the same predicted results, although there are still some errors with the experimental peak pressure and muzzle velocity. The initial gas generation pressure increases more rapid than the predication by the classic interior ballistic. However, the peak pressure coming up later. Simulation results show that the new methods based on the experimental pressure-apparent burning rate model can be used to predict the peak pressure and muzzle velocity of gun propellant charge.

The error of new interior ballistic method based on the experimental pressure-apparent burning rate model is going to be discussed. From the equations of mass burning rate and pressure impulse, obviously, these rules are derived from the closed vessel which is just approximate to the gun bore combustion. Another important factor is the pressure impulse introduced in this model. Although I_k is a constant for a specific propellant under a certain test conditions in closed vessel, it is not the same as the values in the gun. In the closed vessel, I_k is the area under the pressure-time curve along the time axis from the zero point to the maximum pressure-time point. However, in the gun, the actual I_k is difficult to determine in advance. Therefore, the possible choices are controlled by fitting to observed ballistic data.

6. Conclusion

(1) A new experimental pressure-apparent burning rate model is established which are different from the traditional method of form function. The new model bases on the concept of relative pressure impulse. The propellant gas generation rate in the new model is characterized by $\Psi - Z_p$ curve. By this new model, the complicated form function calculation is unnecessary, and the deviation of web size from one grain to another grain can be avoided. Meanwhile, the influences of the pressure on burning rate during combustion process is considered, which can result in the synergistic effect of burning circumstance to increase the gas generation rate in closed vessel and during the combustion process.

(2) Numerical calculation is conducted using the experimental pressure-apparent burning rate model based on the test data of three kinds of propellants. Meanwhile, the obtained numerical simulation results are compared with the calculated result using the traditional form function method. There is a significant deviation of the gas generation rate between them. The traditional calculation method depends on the uniform dimensions and shape of propellant, without considering the influences of the pressure on burning rate during combustion process. Actually, the grain web size varies from one grain to another grain. The new method is not dependent on the form function calculation, and considers the ssynergistic effect of pressure on the gas generation rate in closed bomb and during the combustion process. Therefore, it is more practical to calculate the apparent burning rate.

(3) Interior ballistic prediction results based on the new experimental pressure-apparent burning rate model showed good agreement with the classic interior ballistic prediction though the agreement with the experimental results is still imperfect. The new interior ballistic method is not necessary to calculate the form function of propellant. Therefore, it is easy to be applied to predict some special gun propellant charge while the classic interior ballistic can't be employed.

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