Study on the Mechanism of Ablation Effect of Plasma upon Gun Propellant

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Abstract: In order to study the interaction mechanisms of plasma and gun propellant, the physical and mathematical model describing the ablation effect of plasma upon propellant were put forward based on the double layer dynamic model which was founded by Professor Keidar. The ablation effect of SF-3 propellant, GR5 propellant and ETPE propellant was studied and their ablation mass was simulated with the arc plasma characteristic and the propellant characteristic in the model. The computed values and the experimental at ones are matched well under the ablation action of lower plasma energy. The model can describe the ablation process of gun propellant under the plasma. With increasing of plasma energy the deviation between computed and experimental results becomes larger. The reaction influence increases with the enhancement of plasma energy. With regards to the sensitivity of these propellants under the action of arc plasma, the double-base propellant is the strongest, and ETPE propellant is the weakest.

Key words: physical chemistry; plasma; propellant; ablation effect; combustion
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等离子体对发射药烧蚀作用的机理研究

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摘　要:为了研究等离子体对发射药的点火燃烧作用机理,在Keidar教授处理烧蚀问题的双层动力学模型基础上,建立了用于描述等离子体对发射药烧蚀作用的物理模型和数学模型。研究了等离子体对SF-3发射药、GR5发射药及新型ETPE发射药的烧蚀作用,利用所获得的电弧等离子体特性参数与发射药的特性参数对烧蚀质量进行了数值模拟。结果表明,在较低的电弧等离子体能量作用下,理论计算结果与实验结果具有较好的一致性,所建立的模型能够反映等离子体对发射药的烧蚀作用过程。随着等离子体能量的升高,理论计算结果与实验结果之间的偏差逐渐加大,反应作用因素影响增强。3种类型发射药中,ETPE发射药对电弧等离子体的敏感程度最弱,SF-3发射药对电弧等离子体的敏感程度最强。

关键词: 物理化学;等离子体;发射药;烧蚀作用;燃烧

Introduction

Long shot, high precision, great power is the object of development of gun. ETC (electric thermochemistry) propulsion is a new concept of firing technique. It can enhance the tactical guideline of artillery such as gunshot, precision, power[1]. Different from the general artillery, the plasma ignition has been adopted by ETC gun. The effect of plasma upon gun propellant has great influence on the ballistic performance of ETC gun. The ignition of high energy low sensitivity propellant charge and high loading density propellant charge can be improved based on the predominant ignition performance of plasma. And it is propitious to the ap-

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plication of new generation gun propellant and propellant charge[2-4].

At present study on the effect of plasma upon gun propellant focuses on the enhancing mechanism of burning rate of gun propellant, the multiphase flow model of ignition, and the effect of radiation energy flow upon gun propellant. From the point of view of ignition mechanism of gun propellant, the high temperature ablation effect of plasma upon gun propellant has a great influence on the ignition process. It controls the energy conversion mechanism in the period of ignition. And it is the key point for analyzing the effect of plasma upon gun propellant.

The ablation effects of plasma upon SF-3,GR5 and ETPE were studied based on numerical simulating and experiment in this paper.

1 Numerical simulations

1.1 Physical models

Gun propellant which contains macromolecule component is a kind of energetic material. For describing the ablation effect of plasma upon gun propellant, several hypotheses have been set as follows:

(1) Because of the low heat exchange coefficient and the instantaneous of ignition, the influence of heat exchange which from the propellant surface to the interior of the propellant particle is neglected.

(2) The propellant mass which has been ablated at initiative period lies on the vapour tension of gun propellant under high temperature.

(3) A double layer dynamic model presented by Keidar in 2001[5-6], is adopted to theoretically explain the microcosmic process of ablation. And based on the complicated microcosmic process, a set of equations were founded. A series of correlative parameters can be evaluated . As figure 1, there are two sublayers in the ablation vapour layer between the plasma and propellant. One is the unbalanced dynamic layer (Knudsen Layer), which is near the gun propellant surface, and the thickness of this sublayer is very thin, only two or three free path. And the other is the unbalanced liquid layer, in which the impact of electron and other particles is the main effect, and there is a great difference between the electron temperature and the temperature of heavy particle.

(4) The NC and BAMO/AMMO (macromolecule compound) can not melt-out, which is totally different from the nitric acid ester. So the vapour tension of NC and BAMO/AMMO is supposed to be zero regardless of the temperature of the two compounds.

(5) Once the ablation effect initiates, the ablation production is always homogeneous.

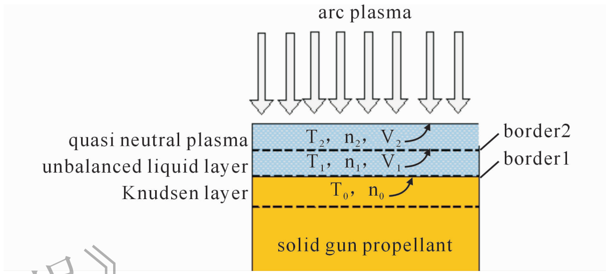

Fig. 1 Physical model of ablation effect of plasma upon gun propellant

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1.2 Mathematic model

The method for dealing with Knudsen layer in the ablation effect of plasma upon gun propellant in this paper was devised by Anicimov[7]. A hypothesis has been set that the distributing function of particle velocity in the Knudsen layer can be expressed as a weighted sum of velocity distributing functions of inside and outside the Knudsen layer. As equation (1):

$$f(x,V)=\gamma(x)f_0(V)+[1-\gamma(x)]f_1(V) \quad (1)$$

Where $\gamma(x)$ is an unknown function, on the surface of the solid material $\gamma=1$, while on the outside border of Knudsen layer $\gamma=0$.

$f_1(V)$ is the function of particle velocity distribution on the outside border of the Knudsen layer. Where the translation of particles have been in equilibrium, so $f_1(V)$ follows the Maxwell velocity distribution based on the excursion velocity V_1.

$$f_1(V)=n_1\left(\frac{m}{2\pi kT_1}\right)^{3/2}\exp\left(-m\frac{(V_x-V_1)^2+V_y^2+V_z^2}{2kT_1}\right) \quad (2)$$

Where $V=(V_x,V_y,V_z)$ is a vector of velocity, and V_1 is the velocity of ablation particles on the outside border of Knudsen layer (border 1 in figure 1), T_1 is the temperature of heavy particles on the outside border of Knudsen layer，and n1 is the density of the particle number.

$f_0(V)$ is the function of particle velocity distribution on the interface of phase change in the Knudsen layer.[8]（A hypothesis has been set that the ablation product will be presented as liquid state at first，and then it will change to vapour，so there is an interface of phase change in the Knudsen layer.）

$$f_0(V)=\begin{cases} n_0\left(\dfrac{m}{2\pi kT_0}\right)^{3/2}\exp\left(-\dfrac{mV^2}{2kT_0}\right),(V_x\geqslant 0)\\ \beta f_1(V) \qquad\qquad (V_x<0)\end{cases} \tag{3}$$

Where T_0 is the temperature of interface boundary（close to the surface of solid propellant），and n_0 is the density of the particle number. The first item is the velocity distribution of the particle which enters into the plasma. And it reaches phase equilibrium with liquid phase before vaporizing. The second item is the velocity distribution of the particles returning to the solid gun propellant surface，and it is assumed that the velocity distribution is in direct proportion to $f_1(V)$. The particle parameters of outside of Knudsen layer can be figured out based on the particle parameters of propellant surface with mass，momentum，energy conservation equations.（The matrix with various order of velocity distribution function $f(x,V)$ is a constant in the whole algebraicspace of velocity. And the first order matrix denotes the mass flow；the second order matrix denotes momentum flow；the third order matrix denotes translation energy flow.）The matrix with various order of velocity distribution function can be expressed as follows. The positive direction in x dimension is perpendicular to the gun propellant surface，and it points to the plasma.

$$\int_{-\infty}^{\infty}V_x f(x,V)\mathrm{d}V=C_1 \tag{4}$$

$$\int_{-\infty}^{\infty}V_x^2 f(x,V)\mathrm{d}V=C_2 \tag{5}$$

$$\int_{-\infty}^{\infty}V_x V^2 f(x,V)\mathrm{d}V=C_3 \tag{6}$$

The integral equations can be figured out using Mott-Smith method. And the equations can be converted into expressions as follows.

$$\frac{n_0}{2\sqrt{\pi d_0}}=n_1V_1+\beta\frac{n_1}{2\sqrt{\pi d_1}}\left[\exp(-\alpha^2)-\alpha\sqrt{\pi}\,\mathrm{erfc}(\alpha)\right] \tag{7}$$

$$\frac{n_0}{4d_0}=\frac{n_1}{2d_1}\left\{(1+2\alpha^2)-\beta\left[(0.5+\alpha^2)\mathrm{erfc}(\alpha)-\frac{\alpha\exp(-\alpha^2)}{\sqrt{\pi}}\right]\right\} \tag{8}$$

$$\frac{n_0}{(\pi d_0)^{1.5}}=\frac{\alpha n_1}{\pi(d_1)^{1.5}}\left\{(\alpha^2+2.5)-\frac{\beta}{2}\left[(\alpha^2+2.5)\mathrm{erfc}(\alpha)-(2+\alpha^2)\frac{\exp(-\alpha^2)}{\alpha\sqrt{\pi}}\right]\right\} \tag{9}$$

The average velocity of heavy particles on the outside border of Knudsen layer，$d_0=m/2kT_0$，$d_1=m/2kT_0$，$\alpha=V_1/\sqrt{2kT_1/m}$，can be figured out by normalization of local sound velocity，viz. $\sqrt{2kT_1/m}$. The function，$\mathrm{erfc}(\alpha)=1-\mathrm{erf}(\alpha)=1-\dfrac{2}{\sqrt{\pi}}\int_0^{\alpha}\exp(-\xi^2)\mathrm{d}\xi$，is an error function.

In the unbalanced liquid layer，the mass，momentum conservation equations of heavy particles can be expressed as equation (10)，(11).

$$n_1V_1=n_2V_2 \tag{10}$$

$$n_1kT_1+mn_1V_{12}=n_2kT_2+mn_2V_{22} \tag{11}$$

Where n_2 is the density of the particle number；T_2 is the temperature of heavy particles on the border 2 in figure 1（Because all the particles in the quasi neutral plasma have been in equilibrium，so the temperature of these particles are all the same，viz. T_2）. Bringing the equations above into accord，dividing out the V_2，expressions can be transformed into equation (12).

$$\alpha^2=\frac{n_2T_2/2T_1-n_1/2}{n_1(1-n_1/n_2)} \tag{12}$$

The function between number density（n_0）and the temperature（T_0）of the particles in equilibrium state on the surface of gun propellant must be confirmed before solving the system of equations.

$$P_V=n_0kT_0 \tag{13}$$

The vapor tension P_v in equilibrium state，when the surface temperature of gun propellant is T_0，can be attained by theoretic calculating or doing experiment.

The enclosed equation system for calculating the parameters of heavy particles in the ablation product vapour of gun propellant is composed of equation，(7)，(8)，(9)，(12)，(13). The un-

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known quantity (n_0, n_1, T_1, V_1, β) can be solved by inputting the parameters T_0, T_2, n_2. Based on the computational solution, the ablation speed of gun propellant can be obtained with equation (14).

$$\Gamma = m n_1 V_1 (\mathrm{kg \cdot m^{-2} \cdot s^{-1}}) \quad (14)$$

The properties, both of plasma and gun propellant surfaces, are considered in the mathematic model above. The ablation speed, obtained based on T_0, T_2, n_2, can reflect the whole process of ablation objectively from the point of view of physical mechanism.

2 Results and discussion

2.1 Simulative calculation

2.1.1 Calculative condition

Table 1 lists the formulation of gun propellant. Table 2 lists the original conditions of simulative calculation.

Table 1 Formulation of gun propellant

Gun propellant	Formulation	Molecular formula per kilogram	Normative creating enthalpy/(kJ·kg^{-1})
SF-3	56%NC, 26.5%NG, 9.0%DNT, 4.5%DBP, 4%auxiliary agent	$C_{24.49}H_{31.61}N_{9.75}O_{33.59}$	−2091.3
GR5	45%NC, 20%NG, 25%RDX, 5%DNT, 5% auxiliary agent	$C_{20.61}H_{28.49}N_{14.29}O_{32.73}$	−197.55
ETPE01	80%RDX, 20%BAMO/AMMO	$C_{17.28}H_{31.16}N_{28.17}O_{22.91}$	296.94
ETPE02	75%RDX, 25%BAMO/AMMO	$C_{18.22}H_{32.20}N_{28.46}O_{21.88}$	301.90

Table 2 Original conditions of simulative calculation for the effect of plasma upon the gun propellant

Gun propellant	Average mass of particle/10^{-26} kg	Vapor tension/Pa	T_0/K	T_2/K
SF-3	2.3367	$0.265\exp(32.9496-10715.4/T_0)$	550	15000
GR5	2.3551	$0.2\exp(32.9496-10715.4/T_0)+0.25\exp(37.5986-15648.3/T_0)$	550	15000
ETPE01	2.3095	$0.8\exp(37.5986-15648.3/T_0)$	550	15000
ETPE02	2.2976	$0.75\exp(37.5986-15648.3/T_0)$	550	15000

Note: The calculation of Vapor tension in Table 2 followed the Clausius Clapeyron equation $\ln P_v = \frac{\Delta_{vap}H_m}{R} \cdot \frac{1}{T} + C$.

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Figure 2 shows the p-t curves of arc plasma in equilibrium state under the discharge of 5, 7, 9 kV. The number density (n_2) of plasma can be figured out based on the original input parameter p_2.

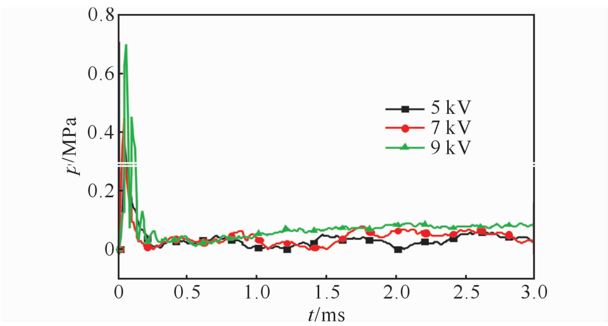

Fig. 2 $p-t$ curves of arc plasma under different discharge voltage

2.1.2 Calculation result

Table 3 shows the simulative calculation result for the effect of plasma upon the gun propellant.

2.2 Experimental result

Table 4 shows the experimental result of ablation effect of arc plasma upon the gun propellant under different discharge voltages.

Table 3 Simulative calculation result for the effect of plasma upon the gun propellant

Gun propellant	Ablation mass/mg		
	5 kV	7 kV	9 kV
SF-3	4.13	4.67	5.87
GR5	3.52	3.98	4.95
ETPE01	3.06	3.42	4.09
ETPE02	2.30	2.56	3.05

Table 4 Experimental result for the effect of plasma upon the gun propellant

Gun propellant	Ablation mass/mg		
	5 kV	7 kV	9 kV
SF-3	4.02	6.60	10.87
GR5	3.20	6.12	8.02
ETPE01	3.82	5.75	11.42
ETPE02	3.45	6.10	10.75

2.3 Discussions and analyses

The calculation result in Table 3 shows that the ablation mass of gun propellant increased along with increasing of arc plasma energy. The sensitivity of gun propellant to plasma reduced gradually keeping to the order of SF-3, GR5, ETPE01, and ETPE02. The experimental result of ablation effect of arc plasma upon the gun propellant in table 4 indicates similar rule. The mathematic model of ablation effect of plasma upon gun propellant can be applied to ablation calculation and estimation of plasma sensitivity. And it will theoretically guide the ignition design of plasma upon gun propellant for ETC gun.

When loading lower discharge voltage, the calculating value of the ablation mass for gun propellant is consistent with experimental result. When loading higher discharge voltage, the calculating value is different from experimental results. And the higher loading discharge voltage, the difference between calculating value and experimental result is bigger. There are two reasons to this phenomenon.

(1) There is a great effect upon calculating result of inputting original parameters, e. g. T_0, T_2, P_v.

The vapor tension is the function of the temperature at gun propellant surface. And it is also an important parameter before the ignition of gun propellant. But it can not be obtained by experiment based on the experimental condition at present. So the vapor tension data have been determined by theoretic calculation in this paper. The effect of surface temperature T_0 upon the reaction speed of ablation have been studied based on the mathematic model above. Figure 3 shows the calculating results of the ablation ratio of gun propellant at 450－650 K.

Figure 3 shows that the ablation ratio of gun propellant will increase with the increasing of surface temperature. The surface temperature has a great effect upon reaction speed of ablation. It also indicates the energy of gun propellant received from plasma. The high surface temperature shows that much of heat flux of plasma has been transported to gun propellant surface through the sheath. So the movement of surface particles is active, and the ablation ratio is high.

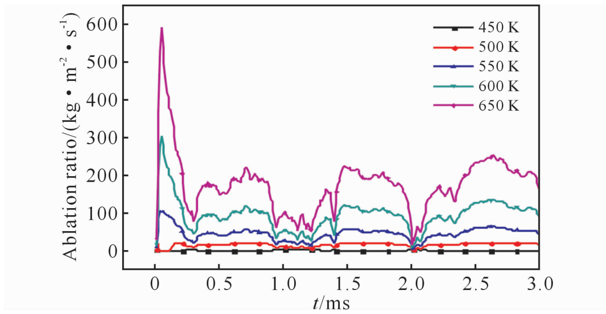

Fig. 3 The effect of original temperature upon ablation ratio of gun propellant

(2) The calculating result of ablation reaction is very different from the experimental result under high discharge voltage. The ablation effect of plasma upon gun propellant rests with chemical reaction rather than gasifying or melting. When the energy of plasma is low, the ablation effect is the main effect of plasma upon gun propellant. The heat exchange and radiation effect of plasma upon gun propellant will enhance with the increasing of arc plasma energy. The ablation reaction model emphasizes the physical process, and the effect of chemical reaction has been ignored. As a result, the calculating value is different from experimental results when loading higher discharge voltage. And the higher loading discharge voltage, the difference between calculating value and experimental result is bigger.

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3 Conclusions

(1) The ablation mass of gun propellant increases along with increasing of arc plasma energy. The sensitivity of gun propellant for plasma reduced gradually keeping to the order of SF-3, GR5, ETPE01, and ETPE02.

(2) When loading lower discharge voltage, based on the model the calculating value of the ablation mass for propellant is consistent with experimental result. When loading higher discharge voltage, the calculating value is different from experimental results. And the higher loading discharge voltage, the bigger difference between calculating

value and experimental result. When loading higher discharge voltage, the factors which affect the effect of plasma upon gun propellant are not only the ablation but also the chemical reaction.

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