THE ACADEMIC STUDY OF THE PERFORMANCE INFLUENCE OF THE GAP CHANGE BETWEEN THE BARREL AND PROJECTILE ON THE GUN INTERIOR BALLISTIC

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Abstract: In the special type of the gun, the gap size between the barrel and projectile is one of the very important parameters for the design of the gun interior ballistics. In order to study the performance influence of the gap change between the barrel and projectile on the gun interior ballistic, a conventional interior ballistic model is established, calculating the influence of the ejection by the gap between the barrel and projectile. On the basis of the model, the theoretical calculation and analysis proceeded for the effect on the performance of the gun interior ballistic by the gap change between the barrel and projectile. The quantitative relation is given between the gap change and the performance of the interior ballistic. The calculation results provide the essential technical information and reference for the design process of the interior ballistic and the propellant charge.
Keywords: interior ballistic, gap change, propellant charge

1 INTRODUCTION

In general, the research of the interior ballistic and the design of propellant charge face those working conditions under high gun pressure (100-600MPa), high propellant combustion temperature (2500-3500k), high projectile velocity (about 1800m/s), high projectile acceleration (1000g-20000g), short projectile moving time alone the gun barrel and the lower powder uniform combustion velocity (0.1-2m/s). With the development of the gun technics, the military manager of the various countries raise their requirements on the general performance and combat power of the gun, therefore this results the design of the interior ballistic and the propellant charge getting in the more difficulty, facing with the rigorous restrain conditions and the requirements of the design input technical indexes. Generally speaking, the design of the interior ballistic and the propellant charge involve the chamber construction, the sizes of the gun chamber, the length of the barrel, the interaction between the projectile and the gun barrel and the mass of the projectile etc [1]. For the howitzer and the armored gun, whatever rifle guns and the slippery guns, the interaction between the projectile and the barrel have the characters of obstruction, thrust and friction. However, the mortar, for one side, because of the gap between the mortar shell and the barrel, there is a phenomena of the ejection of the powder gas with the high pressure and temperature from the gap between the mortar shell (projectile) and the barrel while the mortar shell is moving along with the barrel, So it influences on the maximum pressure and the gun initial velocity, so that the size of the gap is a necessary parameter for the investigator of the interior ballistic. Besides, due to the lower maximum chamber pressure (100-200MPa) of the mortar, it results in the thickness of the body wall of the mortar shell may be designed to thinner form, but it will be more carefully designed, otherwise, it can change the body fame of the mortar shell and enlarge the unregulated change of the gap between the mortar shell and the barrel when the mortar shell moves in the gun barrel, moreover, it also brings anomalous change of the characters of the gun interior ballistic. On the other side, the change of the gap between the mortar shell and the barrel will influence the gun general characters, for example the bigger gap will result in the velocity sharp descending of the mortar shell, further affecting the range of the gun fire, However, it is benefit for the increasing the fire rate, inversely will result the phenomena of the over-pressure of the gun chamber, and bring the difficulties for the loading ammunitions and increasing the fire rate.

2 PHYSICAL AND MATHEMATICAL MODELS

A typical assemble sketch picture of the mortar shell and the propellant charge with the gap are showed in fig 1.

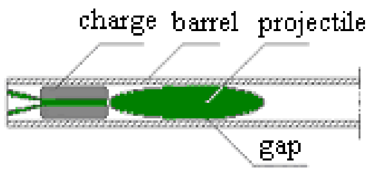

Fig 1 the sketch assemble picture of the mortar shell and the propellant charge

The process of the interior ballistic showed in fig 1, consisting of the process of the primer hitting, which happens at the bottom of the projectile, the ignition process of the basic charge, which happens in the inner part of the tail of the projectile body, the combustion process of the propellant charge which happens around the tail, by igniting with the hot powder gas or particle which ejected from the orifice of the projectile tail, the process of the forming high temperature and high pressure powder gas by combusting the main propellant charge, the process of the projectile movement along the barrel. While the projectile is moving along the barrel, the phenomena of the gas ejection across the gap will happen, that because the chamber pressure was higher than the gas pressure in front of projectile. Summarizing the theory above, the basic hypotheses in the following were made for establishment of the mathematical model and doing the quantitative compute and analyses to the process of the inner ballistic with the gap between the projectile and barrel.

· The propellant charge is ignited and combust simultaneously

· Ignoring the ignition process of the propellant charge and regard the ignited powder as the rapidly combusted powder, which distributed uniformly in the chamber.

· The eject state of the powder gas form the gap is regarded as the state flow.

· The powder combust in the chamber accords with the parallel geometrical combustible law.

· The gas state equation accords with the Nobel-Abel equation.

· The heat loss in the process of the interior ballistic can be corrected by decreasing the powder force.

On the physical basis mentioned above, the mathematical model is established as below:

Before the split of the propellant grain combustion:

$$\frac{dz_i}{dt} = \frac{p}{I_{K_i}} \tag{1}$$

$$\frac{d\psi_i}{dt} = \chi_i\left(1 + 2\lambda_i Z_i + 3\mu_i Z_i^2\right)\frac{dZ_i}{dt} \tag{2}$$

$$\frac{dW_\psi}{dt} = \sum_i \omega_i\left(\frac{1}{\delta_i} - \alpha_i\right)\frac{d\psi_i}{dt} + \bar{\alpha}\cdot\dot{m} + s\cdot u \tag{3}$$

$$\frac{d\rho}{dt} = \frac{1}{W_\psi}\left[\left(\sum_i \omega_i \cdot \frac{d\psi_i}{dt} - \dot{m}\right) - \left(\sum_i \omega_i\psi_i - m\right)\cdot\frac{d\ln W_\psi}{dt}\right] \tag{4}$$

$$\frac{dp}{dt} = \frac{1}{W_\psi}\left[\left(\sum_i \omega_i f_i \frac{d\psi_i}{dt} - \theta\phi qu\cdot\frac{du}{dt} - m\bar{f}\right) - \left(\sum_i \omega_i f_i\psi_i - 0.5\theta\phi qu^2 - m\bar{f}\right)\cdot\frac{d\ln W_\psi}{dt}\right] \tag{5}$$

$$\frac{dT}{dt} = \left[\left(\sum_i \omega_i f_i \frac{d\psi_i}{dt} - \theta\phi qu\cdot\frac{du}{dt} - m\bar{f}\right) - \left(\sum_i \omega_i f_i\psi_i - 0.5\theta\phi qu^2 - m\bar{f}\right)\cdot\sum\omega_i R_i\frac{d\psi_i}{dt}\right] / \sum\omega_i R_i\psi_i \tag{6}$$

$$\frac{du}{dt}=\frac{S\cdot(p_d-R_1)}{\varphi_1\cdot q} \tag{7}$$

$$\frac{dx}{dt}=u \tag{8}$$

After the split of the propellant grain combustion: Formula (2) changed as:

$$\frac{d\psi_i}{dt}=\frac{\chi_{si}}{Z_{K_i}}\left(1+2\lambda_{si}\frac{Z_i}{Z_{K_i}}\right)\frac{dZ_i}{dt}$$

in which:

$$\chi_{S_i}=\frac{\psi_{S_i}-\xi_{S_i}^2}{\xi_{S_i}-\xi_{S_i}^2},\lambda_{S_i}=\frac{1-\chi_{S_i}}{\chi_{S_i}} \quad \psi_{S_i}=\chi_i(1+\lambda_i+\mu_i) \quad \xi_{S_i}=\frac{1}{Z_{K_i}} \quad Z_{K_i}=1+\frac{\rho_i}{e1_i} \quad \rho_i=0.2956\cdot\left(\frac{d_{0_i}}{2}+e1_i\right)$$

The others formula not changed. After the end of the propellant grain combustion:

$$\frac{dz_i}{dt}=0 \tag{9}$$

$$\frac{d\psi_i}{dt}=0 \tag{10}$$

$$\frac{dW_\psi}{dt}=\bar{\alpha}\cdot\dot{m}+su \tag{11}$$

$$\frac{d\rho}{dt}=-\frac{\dot{m}}{W_\psi}+m\cdot\frac{d\ln W_\psi}{dt} \tag{12}$$

$$\frac{dp}{dt}=\frac{1}{W_\psi}\left[\left(-\theta\phi qu\cdot\frac{du}{dt}-m\bar{f}\right)+\left(0.5\theta\phi qu^2+m\bar{f}\right)\cdot\frac{d\ln W_\psi}{dt}\right] \tag{13}$$

$$\frac{dT}{dt}=\left[\left(-\theta\phi qu\cdot\frac{du}{dt}-m\bar{f}\right)\right]/\sum\omega_i R_i \tag{14}$$

$$\frac{du}{dt}=\frac{S\cdot(p_d-R_1)}{\varphi_1\cdot q} \tag{15}$$

$$\frac{dx}{dt}=u \tag{16}$$

in which:

$$I_{K_i}=\frac{e1_i}{u1_i} \qquad W_\psi=W_{0\delta}+\sum_i\omega_i\psi_i\left(\frac{1}{\delta_i}-\alpha_i\right)+\bar{\alpha}\cdot m+S\cdot X \qquad \bar{\alpha}=\frac{\sum_i\omega_i\alpha_i}{\sum\omega_i}$$

$$W_{0\delta}=W_0-\sum_i\frac{\omega_i}{\delta_i} \qquad m=\int_0^t \dot{m}\,dt \qquad \dot{m}=c_d\cdot\rho_j\cdot u_j\cdot s_j$$

$$u_i=\begin{cases}\sqrt{\dfrac{2\gamma}{\gamma+1}\cdot\left(\dfrac{p_d}{\rho_d}\right)} & when \quad \dfrac{p_a}{p_d}\le\left(\dfrac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}\\ \sqrt{\dfrac{2\gamma}{\gamma-1}\cdot\dfrac{p_d}{\rho_d}\left[1-\left(\dfrac{p_a}{p_d}\right)^{\frac{\gamma-1}{\gamma}}\right]} & when \quad \dfrac{p_a}{p_d}\ge\left(\dfrac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}\end{cases}$$

$$\rho_j=\rho_d\cdot\left(\frac{p_a}{p_d}\right)^{\frac{1}{\gamma}} \qquad p_d=\left(1+\frac{1}{3}\frac{\sum_i\omega_i}{\varphi_1 q}\right)^{-1}\cdot p \qquad p_t=\left(1+\frac{1}{2}\frac{\sum_i\omega_i}{\varphi_1 q}\right)\cdot\left(1+\frac{1}{3}\frac{\sum_i\omega_i}{\varphi_1 q}\right)^{-1}\cdot p$$

annotate：i=1，2 respectively represent the ignited powder and the propellant charge; the symbols in the formula shown in literature [2]。

3 COMPUTATIONAL RESULT AND ANALYSIS

3.1 The Computational Result

On the basis of the above establishing model, the corresponding computational program is made, and has done the computational simulation to the process of the interior ballistic for a large caliber mortar in three conditions, which are the puny change and the strong change of the gap between the mortar shell and barrel, and the gap change due to the problem of the intensity of the projectile body structure. The results have been shown in table 1-3 and figure 2-5, in which the computational result of the gap size 0.25mm is regarded as a standard one, the other results are shown in the table 1-3 comparing with it.

Table 1, The influent for the interior ballistic characters in condition of the puny change of the gap

gap mm	Flow coff. C_D	Initial velocity change %	Max. pressure change %	Time of the max. pressure，ms	Oral pressure change %	Oral tem. change %	The flow mass from gap，kg	Oral time ms
0.45	0.50	-1.18	-1.26	3.323	-3.2	-2.3	0.0336	10.47
0.35	0.40	-0.42	-0.39	3.279	-1.1	-0.83	0.02429	10.38
0.25	0.35	1	1	3.255	1	1	0.01904	10.33
0.15	0.23	0.64	0.68	3.218	1.8	1.4	0.01105	10.26
0.05	0.1	1.18	1.26	3.189	3.2	2.6	0.00417	10.2

Table 2, The influent for the interior ballistic characters in condition of the strong change of the gap

gap mm	Flow coff. C_D	Initial velocity change %	Max. pressure change %	The time of the max. pressure，ms	Oral pressure change %	Oral tem. change %	The flow mass from gap，kg	Oral time ms
2.0	1.0	−12.5	−16.1	4.483	−31.5	−27.4	0.1818	12.42
1.5	1.0	−6.6	−8.6	3.815	−18.8	−14.9	0.1064	11.33
1.0	1.0	−5.1	−7.0	3.655	−15.3	−12.0	0.0889	11.08
0.5	0.5	−1.3	−1.3	3.332	−3.4	−2.6	0.0352	10.48

Table 3, the influence for the interior ballistic characters by the gap abruptly is enlarged due to the change of the projectile body structure

The projectile travel m	gap mm	Flow coff. C_D	Initial velocity change %	Max. Pressure change %	The time of the max. pressure，ms	Oral pressure change %	Oral tem. change %	The flow mass from gap，kg	Oral time ms
$0<X\leqslant X_M$	0.25	0.35	-2.0	1	3.255	-14.2	-15.0	0.1019	13.93
$X_M<X\leqslant 1$	0.25-2.0	C_D							
$1<X\leqslant L_D$	2.0	1.0							
$0<X\leqslant X_M$	0.25	0.35	-3.0	1	3.255	-16.3	-17.6	0.1191	14.0
$X_M<X\leqslant 0.5$	0.25-2.0	C_D							
$0.5<X\leqslant L_D$	2.0	1.0							
$0<X\leqslant X_M$	0.25	0.35	-6.6	1	3.255	-34.3	-35.6	0.2196	14.2
$X_M<X\leqslant 0.5$	0.25-5.0	C_D							
$0.5<X\leqslant L_D$	5.0	1.0							
$0<X\leqslant X_M$	0.25	0.35	-11.9	1	3.255	-52.33	-54.5	0.3322	14.54
$X_M<X\leqslant 0.5$	0.25-10.0	C_D							
$0.5<X\leqslant L_D$	10.0	1.0							

Annotate: Xm: the corresponding projectile displacement for the moment of the maximum pressure; L_D: the projectile maximum travel; C_D: the flow coefficient, selected from literature [3] and determined by the gap size.

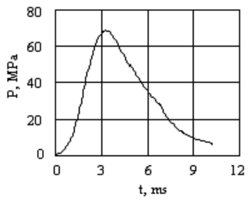

Fig 2, the P-t curve for the gap width 0.25mm

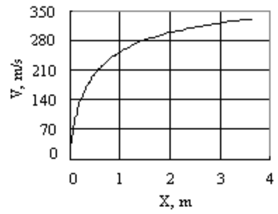

Fig 3, the V-X curve for the gap width 0.25mm

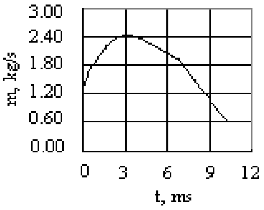

Fig 4, the gas flux curve with time for the gap width 0.25mm

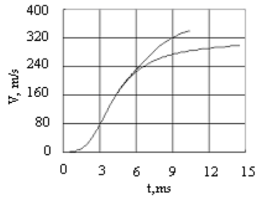

Fig 5, the compare curve of the projectile velocity with the time for the gap width 0.25mm and the last scheme which is shown in table 3

3.2 The analysis of the computational Result

1) From table 1 we could make out, that in the condition of the infirm change of the gap width, the projectile initial velocity will be increased from –1.18% to 1.18%, the maximum chamber pressure will be increased from –1.26% to 1.26%, the oral pressure will be changed between –3.2% to 3.2%, and the gas flow mass across the gap will be decreased from 33.6g to 4.17g along with the gap width from 0.45mm decreasing to 0.05mm.
2) From table 2 we know that if the gap width gets to above 1mm, it will obviously influence the projectile initial velocity and the maximum chamber pressure, the changed rang will be from–5.0% to –15%, at the same time the oral pressure and temperature will be changed approximately from –3% to –30%. So in the development process of the mortar weapon system and the ammunition, despite the larger gap between the mortar shell and barrel is of benefit to loading cartridge conveniently and improving the fire rate, it also brings the notable influence on the character of the interior ballistic.
3) In the table 3 it shows the influence on characters of the interior ballistic in several conditions of the enlarged gap between the projectile and the barrel due to the transfiguration of the projectile body structure when the projectile is moving in the barrel. In the computational process have been made the hypothesis that the projectile body transfiguration start from the moment of the maximum chamber pressure, and after that through some times the meter of the transfiguration get to the maximum value, viz. the gap size get to the maximum. The result of the table 3 shows that the decreasing extent of the initial velocity related to the position of the projectile movement, which corresponding with the maximum transfiguration of the

projectile body structure, and the transfiguration extent of the projectile body structure. In that, the earlier the maximum transfiguration is gotten, the larger mass the gas is vented across the gap, the bigger amplitude of the initial velocity decrease, and the oral pressure, and the same as the bigger transfiguration extent of the projectile body. When the maximum transfiguration extent from 2mm to 10mm, the initial velocity will be changed from –2% to –11.9%, the oral pressure from –14.2% to –52.33%, total mass of the gas being vented gets to 332.2g, comparing to the result of the gap width 0.25mm in the table 1.

4) From fig 2-fig 4 shows that when the gap width is 0.25mm, the shape of the P-t curve and V-x curve are naturally and basically agree with the main properties of the gun interior ballistic . The gas flux will get to the maximum value when the time is equal to 3 ms, at this moment the chamber pressure also gets to the maximum value, and the projectile velocity reach about 80m/s, then the gas flux decreases due to the chamber pressure gradually come down and the projectile velocity increase to the initial velocity.
5) From fig 5 could get that the compare of the change law of the projectile velocity in table 1 with the gap width 0.25mm and in table 3 with the maximum transfiguration of the projectile body. In fig 5 shows that before the moment 6ms the change of the projectile velocity with time was basically same because the same gap width in two conditions, and after the moment 6ms, the gap width will be suddenly enlarged due to the transfiguration of the projectile body shape happened by the reason that no enough structure intensity of the projectile body, it will result in the rapidly increase the gas vent mass, and will make the pressure of the projectile bottom to decrease. There for the projectile velocity will be apparently decrease and the time of the projectile movement will be delayed.

4 CONCLUSION

For the three conditions of the infirm change, the strong change of the gap width between the projectile and barrel, and the gap change due to the transfiguration of the projectile body on the influence of the characters of the interior ballistic have been studied. From the computational and analytical result could make the several conclusions as below:

4.1 The infirm change of the gap width between the projectile and barrel will bring in the small influence on the characters of the interior ballistic. If we make the gap width 0.25mm as a norm, the projectile initial velocity will be changed in range ±1.2% and the maximum chamber pressure in range ±1.3%. From these results we may deduce that the control of the gap width between the projectile and barrel will be very important for the stability of the characters of the interior ballistic.

4.2 The strong change of the gap width will bring apparent influence on the gun oral pressure and the projectile initial velocity. The maximum change of the gun oral pressure and the projectile initial velocity differently reach –52% and –12%. So that the larger gap width will increase more difficulties for the design of the interior ballistic and the propellant charge in order to satisfy the purpose of the gun performance and at the same time will strongly influence the fire distance and power.

4.3 If the projectile body structure was not enough intensity will bring in the large change of the gap width between the projectile and barrel, further seriously influence the characters and stability of the gun interior ballistic, in which the disagreement change of the gap width for every projectile firing will produce the large jumpiness of the projectile velocity above about –12%. There for among the process of the projectile design will consider enough the restrict conditions of the process of the interior ballistic and at the same time enhance the computational analysis for the projectile body material and structure intensity in order to insure the realization of the characters of the interior ballistic and optimization of the projectile body material and the structure design and decrease the cost of the research and production of the projectile.

REFERENCES

[1] M.D.Pocock, Investigation of gas leakage on mortar rounds: Comparison between experiment and numerical modeling, 20th international symposium on ballistics, Orlando. FL, 23-27 September 2002.

[2] M.E.Серебряков，《ВНУТРЕННЯЯ БАЛЛИСТИКА СТВОЛЬНЫХ СИСТЕМ И ПОРОВЫХ РАКЕТ》, ОБОРОНГИЗ, 1962

[3] ZHOU YAN-HUANG, WANG SHENG-CHEN, 《THE PRACTICAL TWO-PHASE FLOW INTERIOR BALLISTICS》, The Ordance industry publishing company, 1990

[4] WANG ZE-SHAN, XU FU-MING, ZHANG HAO-XIA, 《THE PRINCIPLE OF THE DESIGN OF THE PROPELLANT CHARGE》, The Ordance industry publishing company, 1995