Study on Micro Recoil Mechanism of the Weapon with a Nozzle and Two Chambers Separated by a Partition

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Abstract. In order to improve the recoil reduction ability of the weapon without reducing the projectile velocity, the weapon with a nozzle and two chambers separated by a partition is proposed. Taking the 35 mm caliber grenade launcher as the research object, the physical model of its launching process is proposed, and the one-dimensional two-phase flow interior ballistic model is established. MacCormack difference scheme is used to calculate the coupling of multiple physical fields formed by front and rear chambers and nozzles. Compared with the calculation results obtained by using the classical interior ballistic model, the correctness of the two-phase flow interior ballistic model is verified. The effects of the charge amount in the rear chamber and the size of the air guide hole in the barrel on the internal ballistic performance of the weapon with a nozzle and two chambers separated by a partition. The calculation results show that compared with conventional weapons, the recoil impulse can be reduced with maintaining muzzle velocity, and the recoil reduction efficiency can reach 72.27%, which is of great significance for improving weapon performance.

Keywords. Nozzle, two chambers, recoil reduction, two phase flow interior ballistics.

1. Introduction

The weapon with a nozzle and two chambers separated by a partition is a new type of low recoil weapon, which can greatly reduce the recoil impulse with maintaining the muzzle velocity. Based on the expansion wave gun technology [1, 2], the weapon with a nozzle and two chambers separated by a partition is proposed. Although both of them reduce the recoil force of weapon by using the energy of propellant gas, compared with the expansion wave gun, the weapon with a nozzle and two chambers separated by a partition has the following advantages: 1) Because the propellant gas required for recoil reduction is provided by the second chamber rather than from the original chamber, more propellant gas is provided to reduce the recoil impulse of the weapon, and the recoil reduction performance is better. 2) The nozzle is connected with the rear chamber through the air guide hole in the barrel, so the expansion wave generated when the nozzle is opened will not be transmitted to the front chamber, thus affecting the motion of the projectile. 3) The front chamber and the rear chamber are connected by fire holes. The propellant gas in the rear chamber can not only ignite the front chamber, but also provide energy for the front chamber, so as to further improve the muzzle velocity without significantly increasing the maximum chamber pressure of the front chamber. 4) When the pressure of the rear chamber is lower than the front chamber pressure, the propellant gas in the front chamber will flow back to the rear chamber, slowing down the pressure gradient of the rear chamber, and maintaining the...
ability to reduce recoil. Interior ballistic phenomena are physical processes accompanied by high temperature and high pressure of chemical reaction. There are many chambers in the weapon with a nozzle and two chambers separated by a partition and the flow of propellant gas and powder particles between different chambers further increases the complexity of its interior ballistic process. The detailed interior ballistic data can not be obtained through the experiment, so the use of numerical simulation [3-5] to obtain accurate parameters is an effective method.

Jie, SONG et al. [6, 7] studied a dual chamber nozzle recoil reducing weapon, but there are limitations. On the one hand, it does not use two-phase flow numerical calculation, but uses lumped parameter method and Lagrange hypothesis to describe the interior ballistic cycle process with the average value of the variables in the space after the projectile, and does not consider the situation that the propellant gas and powder particles in the front chamber flow back into the rear chamber through the fire hole, on the other hand, because the gunpowder gas and solid particles in the rear chamber flow into the nozzle prematurely, the pressure in the rear chamber decreases too fast, which affects the recoil reduction ability of the weapon.

In this paper, a two-phase flow interior ballistics model of the weapon with a nozzle and two chambers separated by a partition is established. The MacCormack scheme [8-10] is used to solve the coupling field formed by the front and rear chambers, the air guide chamber and the nozzle. It is analyzed that the change of pressure difference between different chambers leads to critical and non-critical flow, and even reverse flow. This change of flow will in turn affect the change of chamber pressure. This process of mutual coupling and interaction is difficult to be observed through experiments.

2. Physical Model
The launching process of the weapon with a nozzle and two chambers separated by a partition can be divided into five stages (figure 1): 1) In the first stage, after the primer is ignited, the propellant gas flows into the air guide chamber. When the propellant gas pressure in the rear chamber reaches the diaphragm breaking pressure, a part of the propellant gas flows into the front chamber; 2) In the second stage, when the pressure of the rear chamber is greater than the limit pressure of the rear spray diaphragm, the rear spray diaphragm is broken, the rear chamber is connected with the nozzle, and the gunpowder and gas in the rear chamber flow into the nozzle and flows out at a high speed through the nozzle to generate reverse thrust; 3) In the third stage, the gunpowder gas in the rear chamber ignites the gunpowder in the front chamber. After the gunpowder gas in the current chamber reaches the projectile starting pressure, the projectile is pushed into the rifling for accelerated movement; 4) In the fourth stage, the pressure of the front chamber is higher than that of the rear chamber, and the propellant gas in the front chamber flows back into the rear chamber; 5) In the fifth stage, the projectile goes out of the muzzle, that is, the aftereffect stage.

![Figure 1. Schematic diagram of launch process of the weapon with a nozzle and two chambers.](image-url)
3. Mathematical Model

3.1. Interior Ballistic Model of Two Phase Flow in Front Chamber

In the equations, \( \rho_g \) is the density of gas phase material; \( \phi \) is the void ratio of gas phase; \( u_g \) is the velocity of gas phase movement; \( A \) is the cross-sectional area of gun bore; \( m_k, \sum m_k \) is the gas generation rate of powder in gas volume and the gas generation rate of various ignition elements; \( p \) is the gas pressure; \( u_{ign} \) is the flow velocity of gas generated by various ignition elements in gun bore; \( \phi_f \) is the resistance between gas and solid phases in unit volume; \( \phi_e \) is the internal energy of gas ratio; \( \rho_s \) is the gas pressure; \( \rho_e \) is the chemical energy of solid phase; \( f \) is the propellant force; \( k \) is the specific heat ratio of propellant gas; \( e_s \) is the stagnation enthalpy of igniter gas; \( q \) is the heat exchange between gas and solid phases in unit surface area.

\[
\begin{align*}
\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} &= \left\{ \frac{H + J'}{H - J} \right\} \\
U &= \begin{bmatrix}
\phi_p A \\
(1 - \phi) \rho_p A \\
\phi_f A (1 - \phi) \rho_f A \\
\phi_e A \left( e_s + u_g^2 / 2 \right)
\end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
F &= \begin{bmatrix}
\phi_p A \\
(1 - \phi) \rho_p A \\
\phi_f A \left( u_g^2 / 2 + p / \rho_s \right) \\
(1 - \phi) A \left( \rho_e u_s^2 + p + R \right)
\end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
H &= \begin{bmatrix}
m_A \\
-m_A \\
m_s, A_f, A_p - f, A_f, A_p + p \frac{\partial A \phi}{\partial x} + (1 - \phi) R \frac{\partial A}{\partial x} \\
-m_s, A_f, A_p + f, A_f, A_p + p \frac{\partial A (1 - \phi)}{\partial x} + (1 - \phi) R \frac{\partial A}{\partial x} \\
-m_s, A_f, A_p + f, A_f, A_p + p \frac{\partial A (1 - \phi)}{\partial x} + (1 - \phi) R \frac{\partial A}{\partial x} \\
f, \mu_s A - AA_f, q - p \frac{\partial A \phi}{\partial t}
\end{bmatrix}
\end{align*}
\]

3.2. Auxiliary Equation

Other auxiliary equations, such as equation of state, burning rate equation, stress equation between particles, interphase heat exchange equation, gas-solid mass, momentum and energy exchange equation between two chambers, can be referred to [11, 12].

4. Analysis of Numerical Results

4.1. Model Validation

In order to verify the accuracy of the mathematical model and the reliability of the numerical calculation method, the chamber pressure curve and projectile velocity curve obtained by previous researchers according to the classical interior ballistic calculation are compared with the calculation results in this paper. As shown in figure 2 and figure 3, the curves are in good agreement, which indicates that the calculation results have a certain degree of credibility.
According to the data in table 1, the error of peak chamber pressure is 5.2% / 2.4%, and the error of muzzle velocity is 2.6%. Because the classical interior ballistics model assumes that all propellants are ignited instantaneously, and the ignition temperature of propellants is not considered, the calculated interior ballistics time is slightly less than that of two-phase flow interior ballistics.

| Two phase flow interior ballistics | Peak chamber pressure/MPa | Muzzle velocity/m.s\(^{-1}\) | Time of peak chamber pressure/ms | Muzzle velocity time/ms |
|-----------------------------------|---------------------------|-------------------------------|--------------------------------|------------------------|
| Classical interior ballistics     | 141.88/138.00             | 438.88                        | 0.76                           | 2.14                   |
|                                   | 134.76                    | 450.62                        | 0.72                           | 2.07                   |

4.2. Comparison of Interior Ballistic Performance of the Weapon with a Nozzle and Two chambers Separated by a Partition and Ordinary Weapon

It can be seen from figure 4 and figure 5 that the time for the pressure in the bore of the weapon with a nozzle and two chambers separated by a partition to reach the peak is 0.854 ms and the peak pressure is 152.171 MPa, while the time for the pressure in the bore of ordinary weapons to reach the peak is 0.764ms and the peak pressure is 141.884 MPa and that the starting time of the projectile of the weapon with a nozzle and two chambers separated by a partition is 0.502 ms and the muzzle velocity is 449.196 m/s, while the starting time of the projectile of the ordinary weapon is 0.401 ms and the muzzle velocity is 438.879 m/s. This is because the weapon with a nozzle and two chambers separated by a partition ignites the powder in the front chamber through the powder in the rear chamber and provides the powder gas energy for the front chamber, while the ordinary weapon ignites the powder by firing the primer. Because the powder gas energy provided by the ignition primer is less than that of the powder gas in the rear chamber, the chamber pressure of the weapon with a nozzle and two chambers separated by a partition is higher than that of the ordinary weapon and the muzzle velocity is greater than that of ordinary weapons.

![Figure 4. Pressure comparison curve.](image1)

![Figure 5. Velocity comparison curve of projectile.](image2)

It can be seen from figure 6 and figure 7 that the peak recoil force of ordinary weapons is -124.440 kN, and the recoil impulse is -106.893 N*s and the peak recoil force of the weapon with a nozzle and two chambers separated by a partition is -25.037k N, and the recoil impulse is -29.642 N*s. The recoil impulse curve of ordinary weapons shows a downward trend, and the degree of decline is very obvious. However, the recoil impulse curve of the weapon with a nozzle and two chambers separated by a partition shows a short rise at first and a slow decline trend. The recoil impulse is essentially the accumulation of recoil force in time. Because the recoil force of ordinary weapons is far greater than that of the weapon with a nozzle and two chambers separated by a partition, this leads to the decline of
recoil impulse curve of ordinary weapons is much greater than that of the weapon with a nozzle and two chambers separated by a partition.

Figure 6. Recoil comparison curve.
Figure 7. Recoil impulse comparison curve.

5. Factors Affecting the Interior Ballistic Performance of the Weapon with a Nozzle and Two Chambers Separated by a Partition

The structure of the weapon with a nozzle and two chambers separated by a partition is more complex than that of the conventional weapon, and the internal ballistic performance is also affected by many factors. Through numerical simulation, the effects of the charge amount in the rear chamber and the size of the air guide hole in the barrel on the interior ballistic performance of weapons are discussed.

5.1. Influence of Rear Chamber Charge

It can be seen from table 2 that with the increase of the charge in the rear chamber, the recoil reduction efficiency of the weapon increases significantly. However, the increase of the charge in the rear chamber also leads to the increase of the pressure difference between the front and rear chambers, which greatly affects the safety performance of the weapon.

Table 2. Comparison of effects of rear chamber charge on recoil reduction efficiency and pressure difference between front and rear chambers.

| Charge amount /kg | Reduced recoil efficiency /% | Differential pressure between front and rear chambers /MPa |
|------------------|------------------------------|---------------------------------------------------------|
| 0.018            | 49.396                       | 20.517                                                  |
| 0.022            | 59.020                       | 30.489                                                  |
| 0.024            | 62.866                       | 42.055                                                  |
| 0.026            | 67.663                       | 61.813                                                  |
| 0.028            | 72.270                       | 96.378                                                  |

5.2. Influence of Barrel Air Guide Hole

It can be seen from table 3 that with the increase of the diameter of the air guide hole, the recoil reduction efficiency does not increase significantly, but the pressure difference between the front and rear chambers decreases greatly. This is because although increasing the diameter of the air guide hole of the barrel makes more gunpowder gas flowing into the nozzle, it will also make the pressure in the rear chamber drop faster, and then affect the combustion of gunpowder in the rear chamber, which in turn will affect the increase of the pressure in the rear chamber, resulting in the failure to improve the recoil reduction efficiency.
6. Conclusion
In order to improve the recoil reduction efficiency of a certain caliber grenade launcher, a one-dimensional two-phase flow interior ballistics model of the weapon with a nozzle and two chambers separated by a partition is established. Through the analysis of the calculation results, it can be proved that the established mathematical model can successfully simulate the interior ballistic process of the weapon with a nozzle and two chambers separated by a partition, which has practical significance for the theoretical analysis of the weapon with a nozzle and two chambers separated by a partition. It can be explained by the simulation of the interior ballistic process that the weapon with a nozzle and two chambers separated by a partition has the advantages of ensuring the initial velocity of projectile and reducing the recoil force significantly. Therefore, the interior ballistic performance of the weapon can be improved to a certain extent by adopting the technology of the weapon with a nozzle and two chambers separated by a partition.

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References
[1] Jianzhuang Z, Jian Z, Di C C and Lei Z 2010 Numerical simulation about rarefaction wave velocity and travel about rarefaction wave gun with two-door breech Proceedings of the Third International Symposium on Test Automation & Instrumentation vol 4 p 1374-7.
[2] Zhi J Z, Di C C, Zhang L and Jiang C C 2009 Modelling and simulation about rarefaction wave gun interior ballistics applying inertial breech 9th International Conference on Electronic Measurement & Instruments p 1091-4
[3] Bougamra A and Lu H 2015 Interior ballistics two-phase reactive flow model applied to small caliber projectile-gun system Propellants Explosives Pyrotechnics 40(5) 720-728.
[4] Cheng C and Zhang X 2019 Numerical investigation of two-phase reactive flow with two moving boundaries in a two-stage combustion system Applied Thermal Engineering 156 422-431.
[5] Cheng C, Wang C and Zhang X 2019 A prediction method for the performance of a low-recoil gun with front nozzle Defence Technology 15(5S1) 703-712.
[6] Song J, Liao Z Q and Li H Q 2018 Study on reducing recoil mechanism of jet gas with laval nozzles with double chamber Journal of Harbin Institute of Technology 501079-87.
[7] Song J, Qiu M and Liao Z Q 2018 Modeling of two jet gas devices and its firing efficiency comparison Transactions of Beijing Institute of Technology 386585-592.
[8] Jang J, Oh S and Roh T 2016 Development of three-dimensional numerical model for combustion-flow in interior ballistics Journal of Mechanical Science and Technology 30(4) 1631-1637.
[9] Jang J, Oh S and Roh T 2014 Comparison of the characteristics of granular propellant movement in interior ballistics based on the interphase drag model Journal of Mechanical Science and Technology 28(11) 4547-4553.
[10] Wang J, et al. 2018 Numerical simulation and optimized design of cased telescoped ammunition interior ballistic *Defence Technology* **14**(2) 119-125.

[11] Weng C S and Wang H 2006 *Computational Interior Ballistics* (Beijing: National Defense Industry Press).

[12] Jin Z M and Weng C S 2003 *Advanced Interior Ballistics* (Beijing: Higher Education Press).